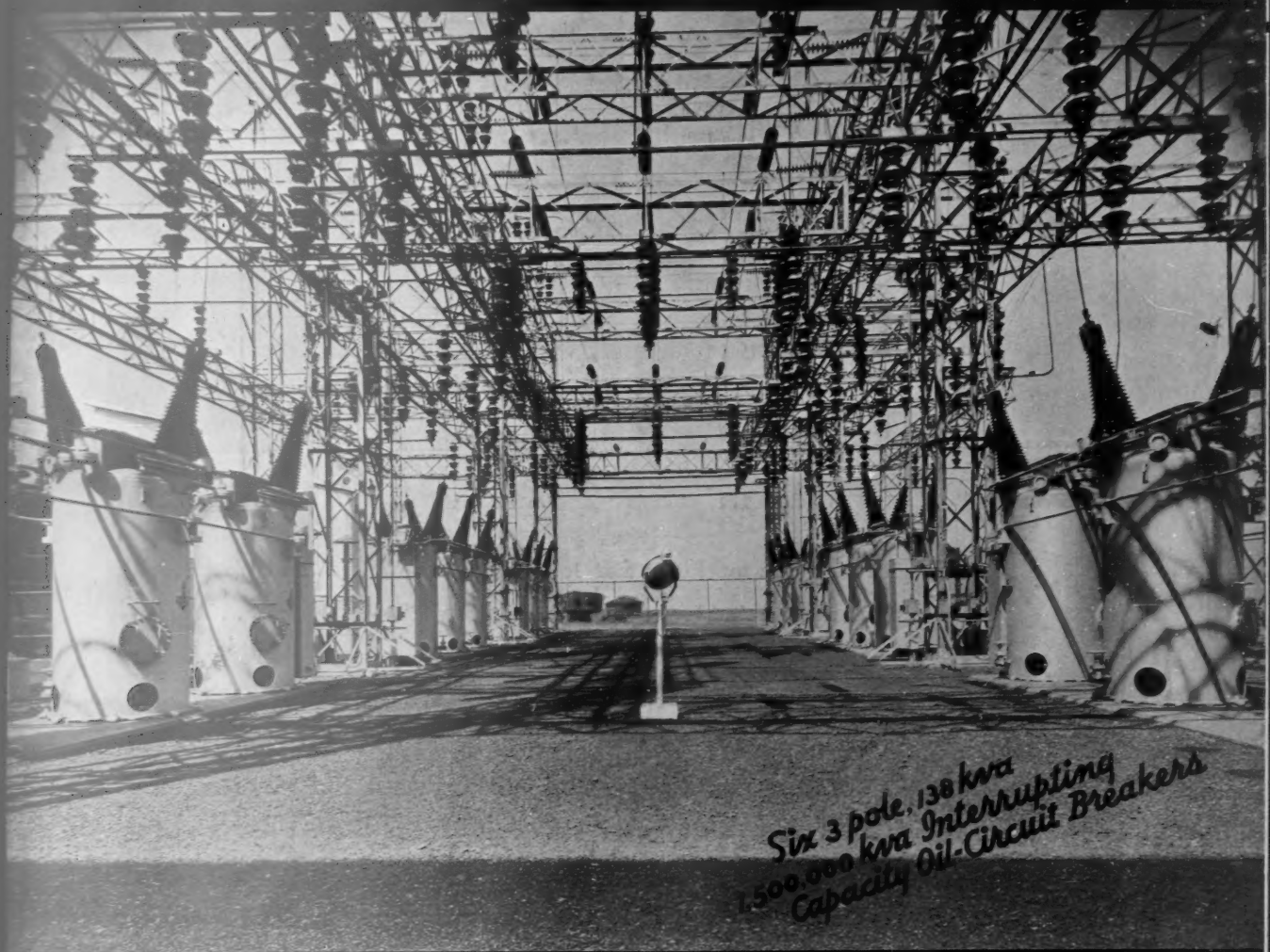
Electrical Review



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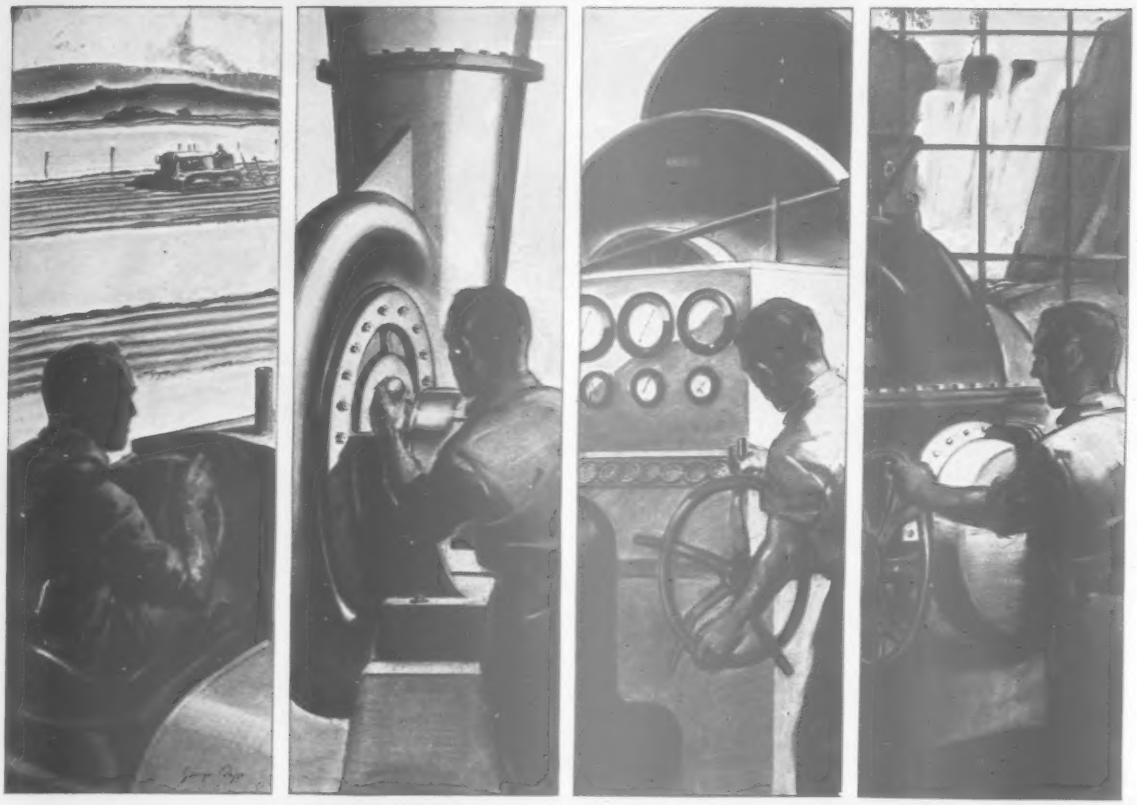

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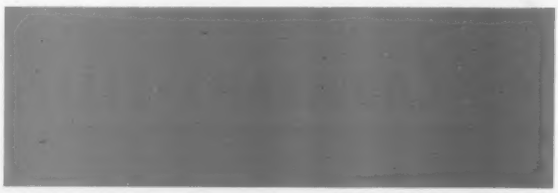

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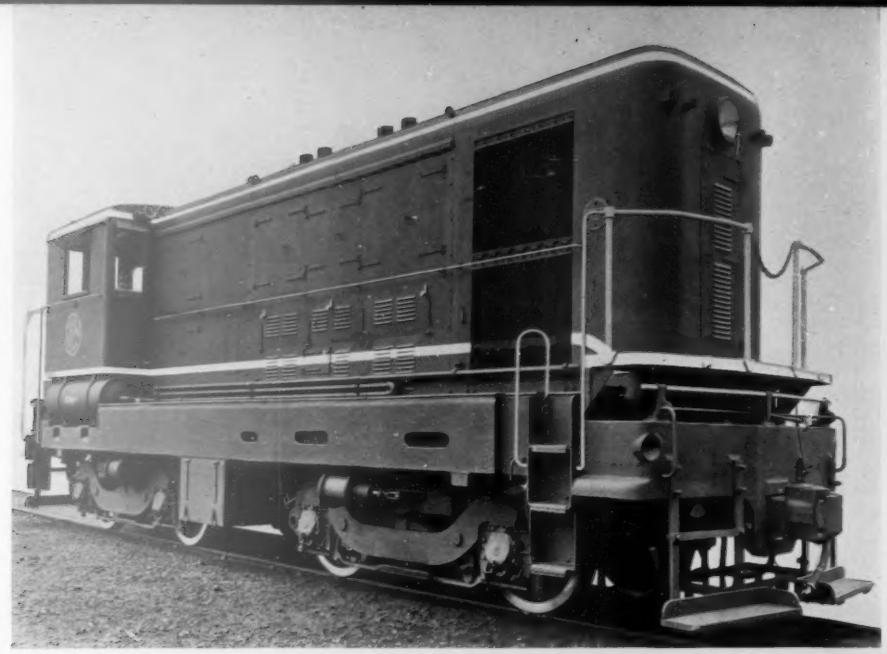


Diesel Electric Locomotives

31499

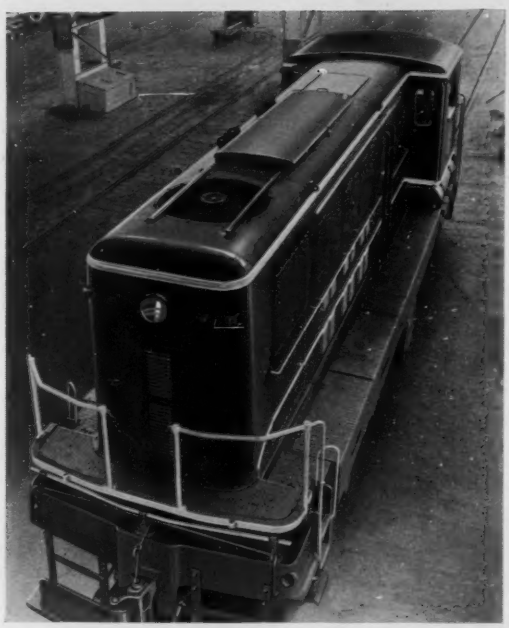
W. GIGER
Railway Equipment Division
Allis-Chalmers Mfg. Co.

DIESEL electric locomotives are today playing an important part in many railway systems, especially for switching purposes. Differing radically from the steam type locomotive which they superseded in many cases, it is only natural that they should create more than a passing interest.

Publicity given them in magazines and newspapers have tended to make the average layman and engineer familiar with their appearance; but of their construction, not much has been said, especially of the electrical equipment.

The locomotive shown on this page is a typical unit. Rated 660 hp it weighs about 100 tons. It has four forced ventilated axle motors that receive power from a d-c main generator, which is directly coupled to a 660 hp, 600 rpm internal combustion engine of De La Vergne design. To keep the cooling water of the diesel engine within the proper temperature limits a blower forces approximately 52,000 cu. ft. of cooling air through the radiators.

For compactness and accessibility practically all of the main power apparatus is placed in a compartment under the locomotive frame. The control equipment for all auxiliary power circuits, such as the air brake compressors, traction motor blowers, radiator fan motor, and the battery charging apparatus are mounted on the main generator. Power is furnished to these circuits by a 40 kw, 125 volt auxiliary generator* directly coupled

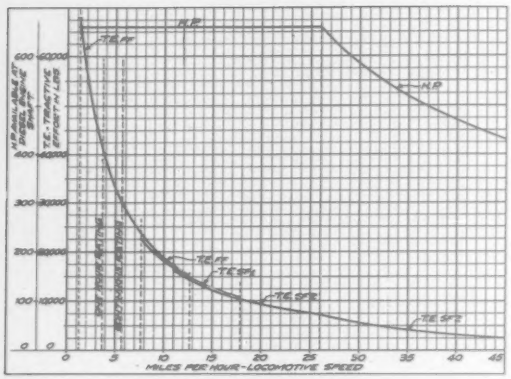


to the main generator. The diesel engine is started from a storage battery, which operates the main generator as a motor until the diesel engine is running under its own power.

The performance curve of the locomotive is shown on page 6. Its rating is as follows:

Maximum starting tractive effort..68,000 lb.
One hour tractive effort.....40,800 lb. at 3.7 miles per hr.
Continuous tractive effort.....29,900 lb. at 5.7 miles per hr.
Maximum locomotive speed.....45 miles per hr.

*See page 8 of this issue.



Performance Curve of Locomotive

Inherently a constant torque machine, the diesel engine is not particularly well suited for locomotive service. Furthermore it must be started by some external power force. As a result because electrical transmission is ideally fitted for this type of application, it is the answer to the question of how to make this type of engine adaptable to railway work.

Keeping in mind that the diesel engine is a constant torque machine, whereas the tractive effort of the locomotive varies from 68,000 lb. at starting to about 2,840 lb. at 45 miles per hr., a ratio of about 27.4:1, it is self evident that to operate a combination of machines to fulfill such seemingly contradictory conditions a special means of control is absolutely essential. This means of control must incorporate two features: (1) It must be such that the diesel engine cannot be overloaded; (2) It must compensate for partial loading conditions by varying the characteristics of the motors and generators.

A comparatively simple control mechanism has been developed to accomplish this two fold purpose. Appropriately named the "servo-field regulator" it ingeniously automatically adjusts the excitation of the main generator, under all operating conditions to such a value that the diesel engine output is about constant. Differentially wound fields in the generator cause the output voltage to droop as the load increases so if the motors draw too much current or if a short circuit occurs, the output voltage becomes zero. This design makes unnecessary the handling of excessively heavy currents by the servo-field regulator, and is another desirable feature for locomotive service as it definitely limits the current that can be drawn by the motors.

The servo-field regulator simply consists of an oil pressure operated main piston, which in turn, by means of a screw and nut connected with it, operates a pair of brushes that run on a commutator and slip ring. The sole function of the brushes riding on the commutator is to increase or decrease a resistance that is in series with the separately excited field of the main generator. The main piston of the servo-field regulator is controlled by a small valve, which is actuated directly from the governor of the diesel engine.

The apparatus is operated by means of oil pressure from the lubricating pump of the diesel engine. Here again the entire function is quite simple. Let us assume that the diesel engine is running at normal load and speed, and consequently the main generator is excited with a certain current value. Now say the locomotive comes to a down grade. The load decreases, and naturally the diesel engine speed increases. This increase

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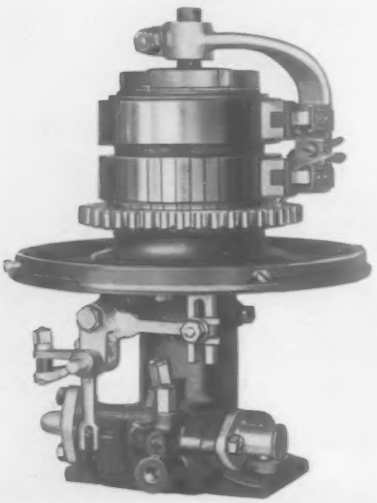

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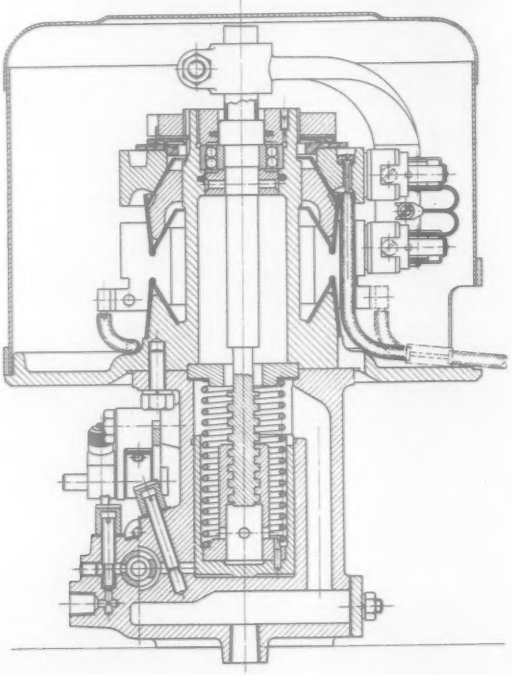

The Servo-Field Regulator Controls the Diesel Electric Locomotive.
Above—the Mechanism with Cover Removed.
Right—Cross-Section

in speed forces the engine governor to change its position in such a way as to decrease the amount of fuel injected into the engine cylinders. Simultaneously with this action, the governor, through the control valve operates the servo-field main piston in such a direction as to increase the excitation of the main generator. This tends to increase its output and consequently that of the diesel engine to which it is directly coupled. This increase in generator output, coupled with the reduced amount of fuel oil which is admitted to the diesel engine, quickly reduces the speed of the engine to the normal value for which its governor is set. A similar regulation cycle is carried out if the diesel engine reduces its speed on account of an increase of its output over the normal value. In this case the excitation of the main generator is decreased and the fuel supply to the engine cylinders increased until normal load and speed conditions are again established.

Since the governors of modern diesel engines are themselves influenced by small changes in speed, it is quite evident that the regulation of the engine load, using the servo-field regulator, is quite smooth, because the corrections that must be made in each case are rather small.

As the servo-field regulator is directly controlled from the diesel engine governor, this method of regulating the output does not depend on the magnetic and electric characteristics of the generator. Any means that may change the speed of the diesel engine will actuate the servo-field regulator.

The following are a few of the factors which would cause the apparatus to react in order to keep the diesel engine output constant:

1. A change in the grade upon which the locomotive is operating.
2. A speed change of the locomotive on level track, due to the tractive effort of the motors being greater than the train resistance.
3. A change in the altitude upon which the locomotive operates, with a consequent drop in the load that the diesel can carry on high levels.
4. A change of the ohmic resistance of railway motors and generator due to heating, which, with increased temperature, would tend to decrease the load.
5. A change in the speed of the diesel engine, that may be caused by plugged-up fuel oil nozzles, and similar mechanical defects that might influence the engine speed.
6. A change of the output of the auxiliary generator. A decrease in the auxiliary generator output immediately increases the output of the main generator in order to keep the diesel engine output constant.

From the above it can be seen that the servo-field regulator is a fully automatic device that continually controls the output of the generator group.

Another important feature of the locomotive is that the traction motors are connected permanently in parallel. This arrangement obviates the necessity of series parallel apparatus and also eliminates the disadvantages of changing the motor combinations, such as a sudden cutoff and reapplication of the power during the transfer, with the inherent possibility of motor commutator flashover during this operation. Parallel connection of the railway motors furthermore greatly reduces the danger of slipping wheels, which are ever a possibility when series connected motors are used.

The remaining parts of the equipment are practically the same as on an electric locomotive. Each motor is, for instance, provided with an over-load relay protection. A main switch group connects the four railway motors to the main generator and at the same time energizes the generator field, whenever the locomotive speed control handle is moved out of its zero position. In case of an overload in one of the motors, the main switch group opens all motor circuits and also interrupts the excitation of the main generator, thereby almost instantly reducing its voltage to zero.

It may be seen, therefore, that even though the diesel engine itself is not well suited for railway drives, the addition of suitable electrical transmission equipment makes it a practicable unit for this type of work.

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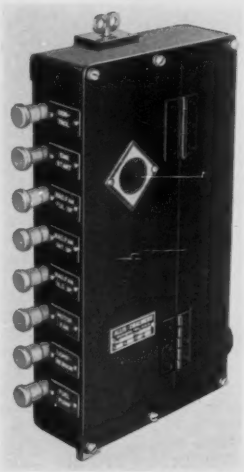

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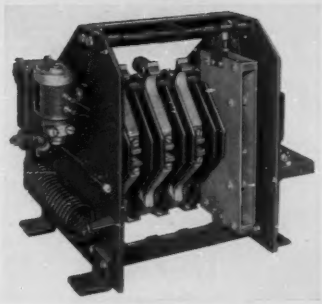

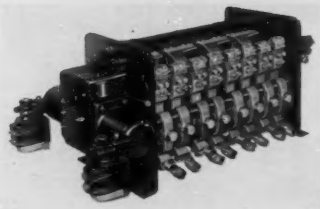

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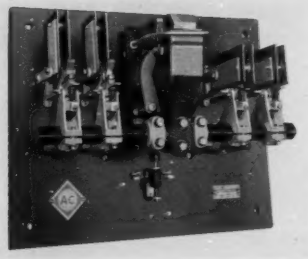


Top—Diesel Electric Locomotive Railway Motor, 600 volts d-c

Left — Push Button Control Box

Right (from top to bottom)— Four Pole Cam Switch Group

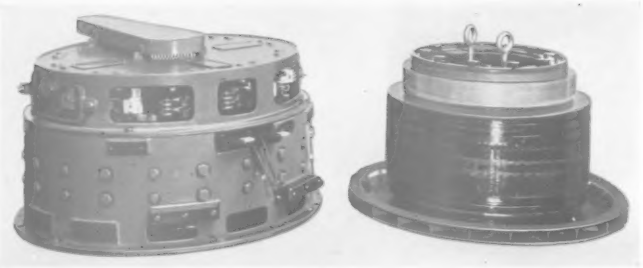
Electro-Pneumatically Operated Reverser

Four Pole Field Shunting Contactor

Diesel Electric Motors and Generators

31078

J. F. SELLERS
D. C. Engineering Division
Allis-Chalmers Mfg. Co.



40 kw, 125 volt Constant Voltage, 300/600 rpm Auxiliary Generator Supplying Lights, Control, Blower Motors, Air Compressor Motors, etc.

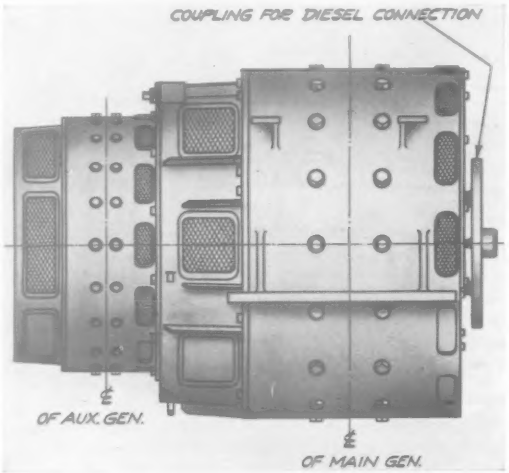
31027

IN THE application of d-c electrical transmission to diesel electric cars and locomotives, the principal considerations are the weight and space requirements. The special d-c generator illustrated was developed for use with a 660-hp diesel engine at 600 rpm, and its weight and volume are about 60% of those of a standard type generator of the same rating. The main generator has a continuous rating of 550 volts at 1200 amp, and the auxiliary generator is 40 kw, 125 volts at any speed between 300 rpm and 600 rpm.

The function of the electrical drive is to change the speed and torque of the engine to the speed and torque required at the axles for the entire range of load and speed schedules of the locomotive. When high starting torques are required, the current is high and the voltage low, and for high locomotive speeds the current is low and the voltage high, the product of the voltage and current always being within the full load horsepower rating of the engine at any engine speed selected by the operator.

This is accomplished by means of a special drooping voltage characteristic of the generator, together with a governor to adjust the generator shunt field when the natural characteristic of the generator deviates from that required. The drooping characteristic of the generator is obtained by means of a differential series field, a separately excited shunt field, and a self excited shunt field. The continuous rating of the locomotive determines the proportions of each field. The differential field is also used to operate the generator as a series motor when starting the diesel engine.

In addition to exciting the main generator, the auxiliary generator is used for battery charging and operating the auxiliary motors of the locomotive.



Main and Auxiliary Generator Assembly

The entire electrical equipment is designed to operate with an 85°C rise at the continuous rating and a 95°C

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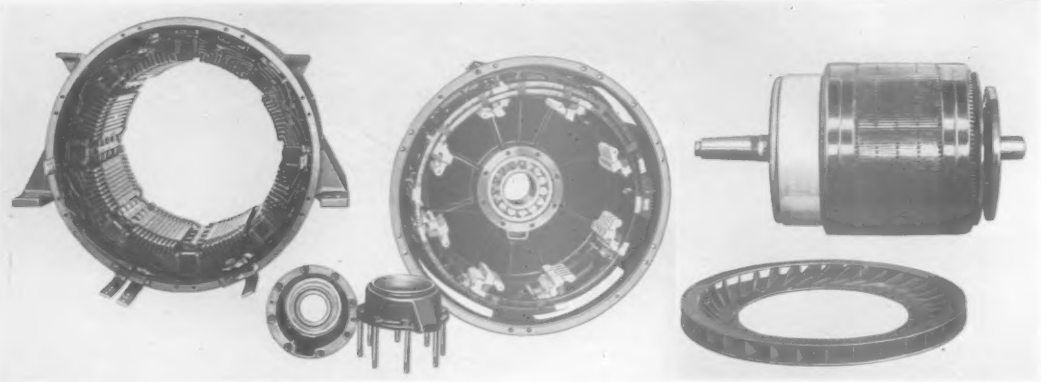


400 kw, 0-600 volt, Variable Voltage, 300/600 rpm Main Generator Furnishing Power to Traction Motors Only

rise at the one hour rating, which means that an actual operating peak temperature of about 145°C is reached. To withstand this temperature, all machines are insulated throughout with mica and asbestos. The generators are self ventilated and have specially designed fans attached to the rear of each armature to obtain a smooth flow of air through the windings. The highest permeability steel obtainable is used throughout the magnetic circuits to keep the sections to a minimum.

Both generators have more poles than would ordinarily be used for these diameters, which reduces the cross-section required in the magnetic parts and also shortens the commutators and the free ends of the armature coils. The generator unit has a single roller bearing, which is located between the main generator armature and the auxiliary generator armature, the auxiliary generator being overhung from the main shaft.

The main shaft is a hollow casting of the largest possible diameter to obtain the greatest stiffness possible to withstand critical engine speeds. The engine bearing supports part of the armature weight through a special rigid coupling. The commutator necks of both generators are solid, and the windings are entirely sealed to prevent breakdowns from accumulation of dirt and brush and commutator wear. Both armatures are rolled in varnish and baked twice, and the frames have the same treatment to prevent rust of exposed steel parts and to seal all the windings against creepage.

The main generator is compensated, which is of prime importance in obtaining light weight, and also enables the generator to satisfactorily commutate the high current required at starting. Auxiliary supports are welded to the top of the main generator frame to hold the regulating resistance in the different shunt fields.

Four series wound motors take the output of the main generator and drive the locomotive over a speed range of 2.7 mph to 45 mph. The shape of the main poles had to be carefully laid out to permit the motors to work over this speed range, the highest portion of which is obtained by two steps of shunting on the series fields. Only the highest grades of laminations and cast steel are used, in order to obtain high starting tractive effort. Mica and asbestos insulation only are used on the armatures and fields, and the armatures are dipped and baked twice—the same as the main generator windings. To be certain the series field coils do not move, each coil is held firmly against a machined surface of the frame by means of four hangers which are bolted to the yoke. The interpole coils are also held against vibration by means of a heavy spring collar next to the pole shoe. Ventilation in this case is of the forced type because of the application of this locomotive.

Engineering Fundamentals

A Department Devoted to the Explanation of Fundamental Principles Underlying Specific Engineering Problems and Their Solution

TRANSFORMER CONSTRUCTION TO WITHSTAND VOLTAGE SURGES

THE SUBJECT of lightning and its effect on transformers has been surrounded by mystery. Actually, the fundamental principles are extremely simple.

These principles are:

A. During a voltage surge from a high capacity source, the total voltage across a transformer winding is determined by apparatus and conditions external to the transformer. Nothing in the internal construction of the transformer can reduce the total voltage.

B. For low voltage surges, sufficient insulation to protect the transformer can easily be provided, regardless of the voltage distribution through the winding.

C. For high voltage surges, if insulation stresses in the winding are to be kept to a value for which proper insulation can be provided, the surge voltage must be distributed uniformly through the winding.

D. To secure this uniform voltage distribution, there are two methods:

1. To design the transformer with such proportions that it inherently has good voltage distribution.
2. To design the transformer with inherently poor voltage distribution, and to put in other means to improve the voltage distribution.

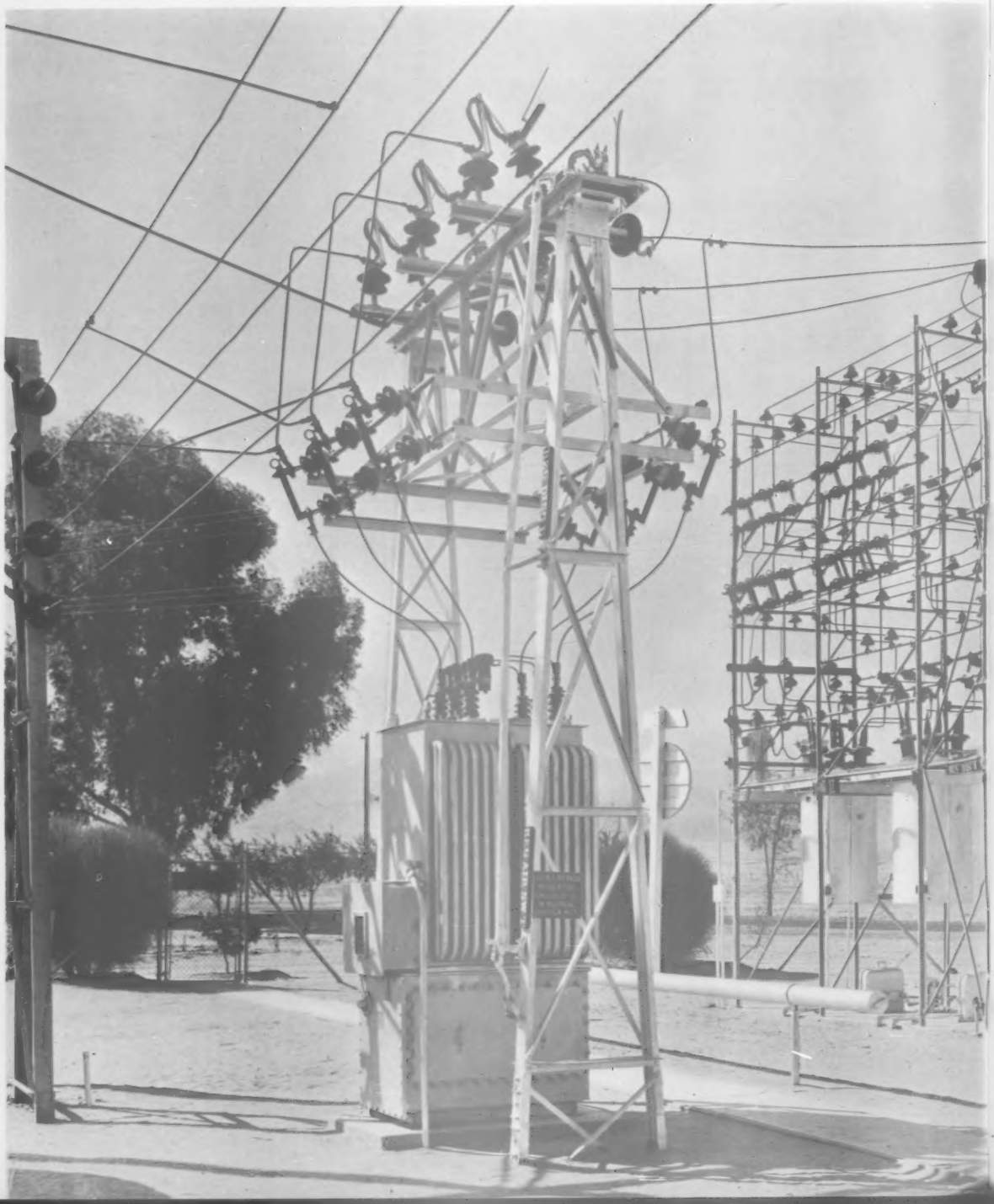
E. When, by securing good voltage distribution, the voltage stresses have been limited to reasonable values, proper insulation must be provided for the existing stresses, with an adequate factor of safety.

Both of the methods for securing good voltage distribution have been successfully used in building transformers to withstand a specified impulse test. The first method (designing for inherently good voltage distribution) is the simpler, for it does not introduce additional stresses in the transformer nor interfere with the insulation of the windings.

In the design of high voltage core type transformers, the first method results in uneconomical proportions and unsatisfactory oil circulation for cooling, and so the second method is generally employed. The inherently poor voltage distribution under surge conditions is improved by the addition of a comparatively large number of shields connected to the line terminals. These shields reduce the voltage stresses in the windings under surge conditions, but they introduce new voltage concentrations of large magnitude between themselves and the coils. The principal disadvantage of this method is the difficulty of providing sufficient insulation for the high voltage concentrations between the shields and the coils without too greatly obstructing oil circulation for cooling.

In the case of shell type transformers, the first method can be used by designing the transformer with proper mechanical proportions. Such a design is practicable, as the resulting proportions (which do not differ greatly from normal proportions for this type of transformer) allow free oil circulation with the usual type of solid insulation between the coils.

STEP VOLTAGE
REGULATOR



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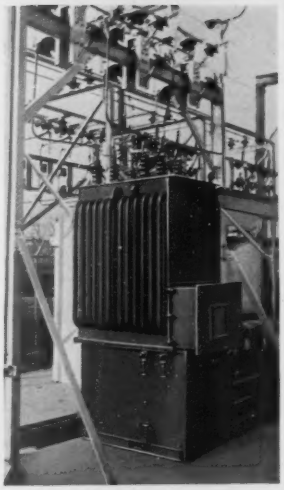

Economic Aspects of Step Feeder Voltage Regulators . . .

J. I. ONARHEIM
Transformer Division
Allis-Chalmers Mfg. Co.

Installation of These Units and Their Relation to Increased Revenue

AS A RESULT of increased loads on feeders, voltage regulation has become an increasingly difficult problem. For over three years utility operating companies have in many cases been installing step type feeder voltage regulators to correct these abnormal voltage conditions.

A careful analysis of the problem will show that on the average circuit step-voltage regulators with small steps, such as ⅝%, will give the same smooth voltage curve as an induction type regulator on a similar circuit. Moreover, on any circuit where the voltage is constantly fluctuating, a ⅝% step regulator using a suitable time delay in its control will produce a more satisfactory curve than an induction regulator. On a fluctuating circuit the primary relay contacts of an induction regulator must be set further apart to avoid excessive operation of the mechanism, and setting the contacts further apart results in poorer voltage regulation. The relay contacts on a step regulator with a time delay contactor can be set for close voltage regulation even on circuits where the voltage is fluctuating constantly. The time delay contactor prevents unnecessary regulator operations on a fluctuating line.

Installing a Step Voltage Regulator vs. Rebuilding Lines

The development of a dependable step voltage regulator offered new possibilities in improving voltage regulation without rebuilding lines. Distribution engineers of many public utility systems have made a complete study of all their lines requiring better voltage regulation and have found that in the majority of cases the step regulator offered the ideal solution. If this type of regulator had not been perfected, it would have been necessary to rebuild many of these lines, for induction regulators with their higher losses, higher exciting current and higher installed prices would have prohibited their use in improving voltage regulation. In other cases, because of high line voltage insulating transformers would have been required with the induction type regulator. These are not necessary with the step type regulator. Insulating transformers would have, of course, added considerably to the total investment cost.

Step feeder voltage regulators are often purchased due to the saving in cost between the installed regulators and the cost of rebuilding the lines but this saving is not the only factor in favor of step type units. The time required to install a regulator will always be less than the time required for rebuilding the line, and since it is not necessary to employ the entire force of linemen when step regulators are installed, the line crews

can be used on line extension operations. Another important factor that should also be considered is that even after a line is rebuilt there still remains a considerable voltage drop at full load, due to line reactance which is not materially affected by increasing copper sizes. For example, doubling the conductor size decreases the reactance less than 15%. Even after larger copper has been installed there still remains some resistance drop, as it is not economical to increase the copper size to a point where the resistance drop can be neglected entirely in calculating line regulation. Realizing that step regulators are revenue builders, utility companies today are installing them on all important feeders, with the result that at present there is a rapidly increasing demand for step voltage regulators. The loads on the majority of feeders have increased materially in recent months, due to the gradual increase in domestic loads together with the present increased demand from industrial loads. This allows utilities an excellent opportunity to study the economics of rebuilding lines vs. step voltage regulators.

The following example illustrates the advantage of installing a step regulator over rebuilding a line. The average rate for electric power in this country is about 5½ cents per kwhr, but in calculating values of increased revenue on feeder circuits, the average rate should not be used. The rate per kwhr is usually on a sliding scale with a lower rate per kwhr for higher consumption above a certain demand rate. A value of 3 cents per kwhr will, therefore, be assumed for this problem.

The following is based on an actual regulator installation and illustrates the point which induced this utility to decide on step regulators. An 11,500 volt, 3-phase, 50-ampere regulator supplies power to 10,000 lamps rated at 50 watts each, assuming that 50% of the load through the regulator is lighting load. If there is a 12% maximum voltage drop, or an average voltage drop of 9%, and the lamps are operated for 1,200 hours per year, a 14% reduction in the power consumed will result. The loss of revenue will be 25.2 cents per lamp year, or $2,520 loss for 10,000 lamps. The regulator on this line paid for itself in increased revenue alone in one and one-half years, which represents a return of 66% per year on the regulator investment. The decided advantage of the regulator installation can be seen from the fact that rebuilding this line to a point where the voltage would have been satisfactory would have cost about three times the amount paid for the regulator installed. With an average voltage drop of 9%, the power taken by lamps is reduced 14% and the candle power, in turn, is reduced 28%. Thus, not only is the utility's revenue reduced, but the consumer receives 28% less light. This particular power company was well pleased with the performance of the step voltage regulator and later purchased eleven more step regulators for other feeders on ths system.

Constant voltage is necessary to sell electric ranges and other electrical appliances for household use, for electric ranges must heat and cook rapidly if they are to receive an equitable share of the total household range sales. Where satisfactory voltage is available, a large majority of housewives would purchase the electric range, but the consumer will not purchase additional household appliances if the voltage at his outlet is already below a satisfactory level. This attitude on the part of a customer retards the normal growth of power demand. The utility companies that are supplying constant voltage at consumers' outlets are receiving increased revenue from the sale of additional appliances and also increased revenue from the larger power demand.

One method that has been used by some companies to overcome the extremely low voltages during peak load has been to raise the voltage at light loads 5% above normal. When the circuit is fully loaded, the voltage may be 5 or 10% below normal. This increase of 5% in voltage above normal is of course objectionable as it reduces the life of incandescent lamps about 47%.

A complete study of each line will usually prove that a step regulator will pay for itself in a comparatively short time. Many actual cases have shown that regulators will pay for themselves in from one to three years. In addition to the increased revenue for the utility due to correct voltage, the power users receive constant voltage at their outlets at all times. By installing regulators, line rebuilding may be put off for many years, and the load growth on some lines may level off so that rebuilding will never be required.

Single-Phase Regulator vs. Three-Phase Regulators

Three-phase regulators can be used on most three-phase systems instead of individual single-phase regulators, with a resultant saving in cost of equipment and installation. The load on the three phases in many cases is distributed so that the regulation drop on any one line is reasonably close to the regulation drop of either of the other lines for any given period. Even where there is an appreciable unbalanced condition, a saving in regulating costs may be obtained by rearranging the circuits or by tolerating a certain amount of difference in voltage on the three phases.

On lines where the type or the amount of load is radically different in the three phases, then, of course, three single-phase regulators for Y operation should be used. This will allow each regulator to raise or lower the voltage on any phase as required by changes in load on that phase.

Three single-phase regulators will cost 30% to 60% more than one three-phase regulator for a given load. The utility engineer must decide if the difference in regulation in the three-phases is great enough to warrant the expenditure of the additional capital for three single-phase regulators. The saving in installation cost should not be overlooked.

A study of the costs on many single-phase systems will prove that the installation of a single-phase voltage regulator will be less expensive and more satisfactory than rebuilding the line to a three-phase system, or rebuilding the line with larger copper.

Large Regulator vs. Several Small Regulators

One large regulator may be used to supply any area where the total full load drop on any part of the system does not exceed the voltage drop on some other part of that system by more than 4% or some other percentage that is satisfactory and economical for that load area. Where the voltage drop in different parts of the system varies more than a reasonable amount, several small regulators should be installed. This arrangement will insure constant voltage on each load area.

One large regulator may be used to maintain proper voltage for a majority of the branches in a given area; however, the voltage on one or two of the branches may fluctuate over a wider range than other branches in the same area. For this condition several small regulators may then be installed on these branches which have the extreme voltage fluctuations. Often the branch regulator can be used to advantage on these circuits where the total regulation drop need not be corrected more than 10%.

To illustrate the saving in investment, consider the price difference between one large regulator and three small regulators for a given load. Three 50 ampere,

11,500 volt, three-phase regulators will cost almost twice as much as one 150 ampere, 11,500 volt, three-phase regulator. A careful study should be made on each system where step regulators are to be installed to determine the advisability of installing one large regulator or several small regulators.

Branch Feeder Regulation

While the station type and distribution type regulators were being developed, an even less expensive feeder voltage regulator was developed for small branch lines where the highest degree of regulation is not required and where less range of regulation is needed. The voltage changes in this branch regulator are made in 1¼% steps, and it is available in three-phase units as well as in single-phase units.

These units cover a total range of 10% in regulation in eight 1¼% steps. Connections can be very easily changed in the field without removing the regulator from the pole to cover any one of the following ranges:

10%	Boost	0%	Buck
7½%	Boost	2½%	Buck
5%	Boost	5%	Buck
2½%	Boost	7½%	Buck
0%	Boost	10%	Buck

The branch units may be used on any line within the rating of the regulator where the voltage need not be corrected more than 10%. Some load areas will not require the full 20% regulation available with station and distribution regulators. The investment required for the larger regulators would not be justified for many load areas. The voltage drop may not exceed 10% except at very brief intervals and the branch regulator with its 10% range will usually correct for most of the regulation drop in the line. The balance of the voltage drop may be tolerated due to the saving in total installation cost of the branch regulator over the cost of the station and distribution regulator.

Consider, for example, a 6900 volt single-phase feeder where the maximum voltage drop is 9% and the average voltage drop is about 7%. Assuming that 60% of the total load is lighting and that the total load through this regulator is 173 kva or 25 amperes, this installation would require a 6900 volt 17.3 kva regulator. With 60% lighting load on this regulator, power will be supplied to 2,076 lamps rated 50 watts each. Again assuming 1,200 hours service per lamp year, with an average voltage drop of 7%, the wattage taken by incandescent lamps will be reduced 11%, or 6.62 kw hours per lamp year. At 3 cents per kw hour, a loss in revenue per lamp year will be 20 cents. The loss for the 2,076 lamps will be $415.20. This regulator would make possible an increase in revenue of $415.00 per year on an investment of $887.00, which is a return of more than 46% on the investment. Furthermore, with an average voltage drop of 7%, the customer would receive 23% less light. This example is typical of many actual conditions, and some circuits will show even a larger return on a branch regulator investment.

In conclusion, a few observations might be considered pertinent.

1. After operating engineers have observed the performance step regulators and have studied the savings in investment costs, and noted the increase in revenue, additional step regulators have usually been installed.

2. Operating companies have improved their systems to the point where continuous service is assured. Today these same companies are in a position to greatly improve the quality of this service by installing step voltage regulators.

3. The increase in revenue obtained by improved voltage due to the installation of step regulators will usually pay for the equipment in a short time.

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Rural Line Installation—
Branch Step Voltage Regulator

Fig. 1—One of Two 1000/2000 kw, 250/500 volt Rectifier Tanks with Control and d-c Switchgear in Plant of Westvaco Chlorine Products, Inc. 30877

Rectifiers Have Been Successfully Used in Foreign Electrolytic Plants for Years . . . But Not Until 1934, When Westvaco Chlorine Products Installed a Rectifier, Were They Used for This Service in the United States

W. E. GUTZWILLER
Rectifier Division
Allis-Chalmers Mfg. Co.

First Rectifier Installation In an American Electrolytic Plant

MERCURY ARC power rectifiers have been successfully and extensively used for years in European and Canadian electrolytic plans where there are today over 400,000 kw in commercial service supplying aluminum, zinc, hydrogen and chlorine-caustic cells. About two years ago the first rectifier installation was made in an American electrolytic plant.

In 1934, when Westvaco Chlorine Products, Inc., needed additional converting equipment for their 250 volt Chlorine-Caustic plant, the management, recognizing the economical advantages of rectifiers and their future importance as a converting unit, decided to install a 2000 kw rectifier in order to gain experience with this modern type of converting apparatus. This first unit was temporarily installed in their South Charleston, West Virginia plant, and was put in commercial service the early part of September, 1934.

This unit was in continuous twenty-four hours a day service until June, 1936, when it was removed to a new and permanent substation.

Description of Equipment

Inasmuch as the installation was the first of its kind in the United States, a short description of the equipment and its performance records should be of general interest.

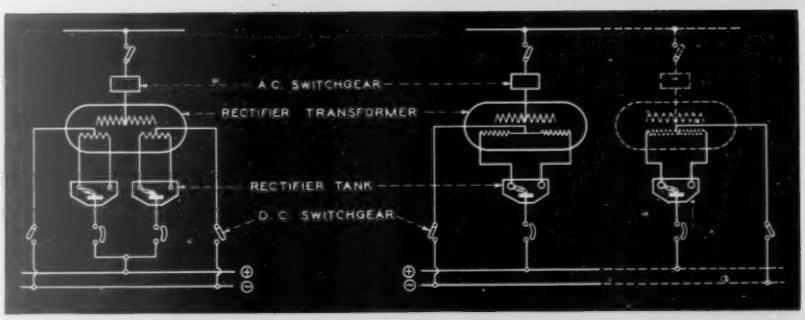
The principal parts of the rectifier unit consisted of two grid controlled rectifier tanks with their auxiliary apparatus. Each tank was rated 4000 amp, 250/500 volt d-c, 1000/2000 kw. The two tanks were supplied from a common 2000 kw, 2300 volt, 3-phase, 60 cycle outdoor type transformer.

In order to explain the reason for the two voltage and kilowatt ratings of this rectifier, it may be well to briefly review the basic inherent characteristics of mercury arc rectifiers. The conversion efficiency of a rectifier tank is practically constant at all loads. This is accounted for by the fact that the kw loss in the rectifying arc, which is a direct measure of the efficiency, is approximately proportional to the rectifier d-c output. The a-c voltage supplied to the rectifier and the rated d-c voltage have little to do with the rectifying process. Rectifiers are rated according to current output. Consequently, the kw rating of a given type of rectifier increases about proportionally with the d-c voltage. Since the arc loss is not affected by the operating voltage, the higher the rectifier efficiency the higher the d-c voltage.

The Westvaco engineers took full advantage of this peculiar characteristic and had the transformer of this first unit arranged with a double secondary winding. This allows the two 4000 amp rectifier tanks to be fed in parallel furnishing 250 volts d-c, amounting to 1000 kw each, or 2000 kw total. A single line diagram of this arrangement is shown in Fig. 2a. The secondary windings also may be connected in series and thus supply one rectifier tank only at 500 volts, 4000 amp, equal to 2000 kw, as shown in Fig. 2b. In doing this it was the intention of the Westvaco Engineers that if desired at some future date, twice the number of chlorine cells

Fig. 2a (left)—Parallel Connected Secondary Windings for 250 volt operation. (Initial Installation)

Fig. 2b (right)—Series Connected Secondary Windings for 500 volt Operation. Dotted Lines Show Additional Equipment Required to Double k-w Capacity



could be connected in series and thus operate at 500 volts d-c with an appreciable gain in efficiency and doubling of the rectifier capacity. This arrangement has the advantage that the substation output can be doubled at the expense of only one additional 2000 kw transformer and one set of a-c switching equipment. The dotted lines in Fig. 2b show the additional equipment required for doubling the rectifier output.

The two rectifier tanks are provided for voltage control by means of energized grids in the arc-path. The total voltage range obtained with this control is approximately 15% of rated voltage. This control was essential due to the necessity of paralleling the rectifiers with a d-c bus, to which are connected four 3150 kw rotary converters, one 1500 and one 750 kw motor generator set.

The rectifier tanks are provided for water cooling by means of a closed recirculating cooling system and a water-to-water heat exchanger. This method of indirect cooling of rectifiers is now commonly used. Distilled or soft water is recirculated in a closed system, consisting of the rectifier tank, the pipe lines, and the heat exchanger, by means of a motor driven water pump. The recirculating water is cooled in the heat exchanger by means of cold, raw water which flows through the cooler jackets and is discharged to the drain. The flow of raw water is regulated by a thermostatic valve having its control element in the hot branch of the recirculating water. A schematic diagram of this recirculating cooling system is shown in Fig. 3. The high vacuum pump on the rectifier, which is of the mercury vapor type, is cooled directly with raw water. Fig. 4 shows a typical factory-assembled water-to water heat exchanger with circulating pump, temperature indicating, control and protective apparatus. An expansion tank is provided to permit expansion and priming of the recirculating water and to serve as a reservoir for make-up water. With this arrangement the same cooling water is used over and over again and raw water, which in this case is pumped from a river, does not get in direct contact with the rectifier tanks. The cooler tubes are arranged so that they can easily be flushed out without interfering with the operation of the substation and are made of corrosion-resisting metal.

The 2300 volt a-c power to the rectifier transformer is controlled by a cubicle type oil circuit breaker located in the near-by power house, and remotely controlled from the rectifier substation.

There is a 6000 amp, single pole solenoid operated d-c breaker connected in the positive lead of each rectifier tank. The negative lead is provided with a 6000 amp knife switch.

All the rectifier auxiliaries are supplied from a control transformer bank, consisting of three 7½ kva single-phase, 2300/230/115 volt transformers.

The rectifier equipment was temporarily installed in an available building adjacent to the rotary converter room. The total inside floor space of the rectifier substation is 16½ x 31½ ft. Fig. 1 shows one-half of the rectifier room with part of the control board to the left and one of the rectifier tanks in the center. The water-

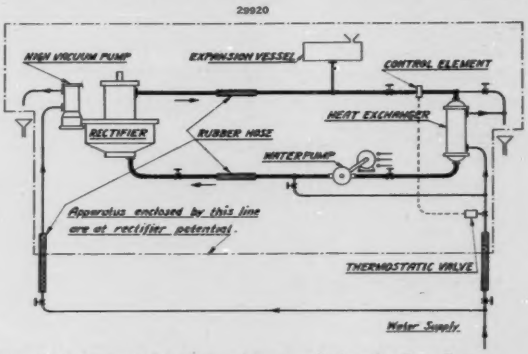


Fig. 3—Schematic Diagram of Recirculating Cooling System with Water-to-Water Heat Exchanger

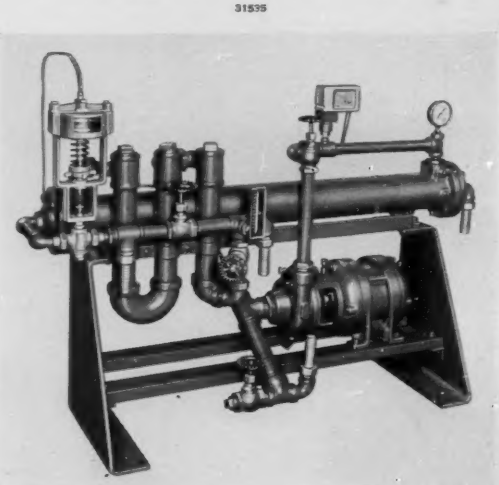


Fig. 4—Typical Factory Assembled Water-to-Water Heat Exchange Unit for Indirect Cooling of a 1000 kw Rectifier

to-water heat exchanger and circulating pump is located to the right of the rectifier. The 6000 amp, single pole d-c breaker and knife switch for one rectifier are visible in the right-hand corner of the substation.

Starting and stopping of the rectifier unit is accomplished by simply closing and opening the a-c and d-c breakers and the control switch for the arc-striking device, and at the same time starting or stopping the cooling water circulating pump. There is no regular attendant in this rectifier substation. The operator of the adjacent rotary converter room makes an inspection of the rectifier station once every hour in order to take log readings and to make an occasional adjustment of the rectifier load with the grid control rheostats. The operating engineers consider a maximum of three inspections every twenty-four hours ample for satisfactory operation of a rectifier of this type.

The major protective devices of this rectifier unit consist of a-c overload and d-c reverse current protection, protection against vacuum and cooling water failure and excessive temperature in rectifier and transformer.

Operating Records

The operating staff reported that during the twenty-one months commercial operation of this rectifier there was no substation shutdown which could be attributed to failure of the rectifier equipment. In spite of the use of river water for cooling, which at times contains considerable foreign matter in suspension, the water-to-water heat exchangers have never been opened for cleaning. Two or three times per day the cooling water is turned on full force momentarily in order to flush out any sediment which may have collected in the tubes of the coolers.

In spite of the fact that the pressure in the water system at times is subjected to wide fluctuations, there was no service interruption due to insufficient supply of cooling water.

The operators consider the grid control in this installation to be as reliable as the field control on d-c generators. No arc-backs in the rectifiers have been recorded during the twenty-one months of commercial operation, nor have a-c line troubles in any way directly affected the rectifiers.

It is interesting to note that at the relatively low d-c voltage of 260 volt the overall conversion efficiency of the rectifier substation has been above 90%.

The maintenance cost during the twenty-one months was negligible and consisted mainly of replacements of a few small control resistors and the furnishings of a small amount of make-up oil for the vacuum pumps and make-up mercury for rectifier seals.

As a result of the highly satisfactory performance of this initial rectifier installation, Westvaco Chlorine Products, Inc., has purchased two additional rectifier sets, each rated 3000 kw, 500 volts d-c. Simultaneously with the installation of this new equipment the two old 250 volt rectifier tanks and their transformer were reconnected to 500 volts, thereby raising the rating per tank from 1000 to 2000 kw with a 5% increase in conversion efficiency. A second 2000 kw transformer was also purchased to take care of the increased output of the old tanks.

These first mercury arc rectifiers used for electrolytic work have demonstrated beyond all doubt their suitability and economy for electrolytic work.

They have been responsible for a number of similar installations, all of which were made subsequently in American chlorine-caustic plants, aggregating a total capacity of over 25,000 kw, and ranging in voltages from 500 to 1000 volts d-c. While up until recently 250 volts has been considered the maximum safe voltage for chlorine-caustic cells, within the short period of two years the use of rectifiers has brought about a radical departure from the conventional 250 volts, and voltages of 500 and higher are now considered entirely satisfactory and safe for chlorine-caustic plants.

SUMMARY OF OPERATING DATA ON WESTVACO RECTIFIER INSTALLATION

(Totals and Averages for 21 Months Operation)

Total 2300 volt a-c input to rectifier transformer	31,303,200 kwhr
Total 2300 volt a-c input to rectifier control transformer	179,680 kwhr
Total 2300 volt a-c input into rectifier and auxiliaries	31,482,880 kwhr
Total rectifier d-c output (both tanks)	28,375,300 kwhr
Total conversion loss, including power consumption of rectifier auxiliaries	3,107,580 kwhr
Overall ac-dc conversion efficiency, including rectifier and auxiliaries	90.14%
Average d-c operating voltage, approximately	260 volts
Guaranteed overall full load efficiency at 250 volts	88.4%
Total time rectifiers were in commercial operation during the 21 months' period (estimated)	15,200 hours
Average d-c load of rectifier set (estimated)	1870 kw
Substation load factor	93.5%
Total power consumption of all rectifier auxiliaries, metered on 2300 volt side of control transformer, in per cent of station input	.57%

The principal advantages over conventional rotating equipment which are mainly responsible for the successful introduction of mercury arc power rectifiers in the electrolytic field on such a large scale are:

- Low maintenance and operating cost due to immunity to chemical fumes.
- Absence of heavy rotating parts, brushes, commutators and bearings.
- High overall conversion efficiency.
- Simple voltage control and protection by electrically energized grids.
- Unusual stability during a-c system disturbances.
- Easy and instantaneous starting and no reversal, permitting remote control of substations from cell rooms.
- Practically unlimited life.

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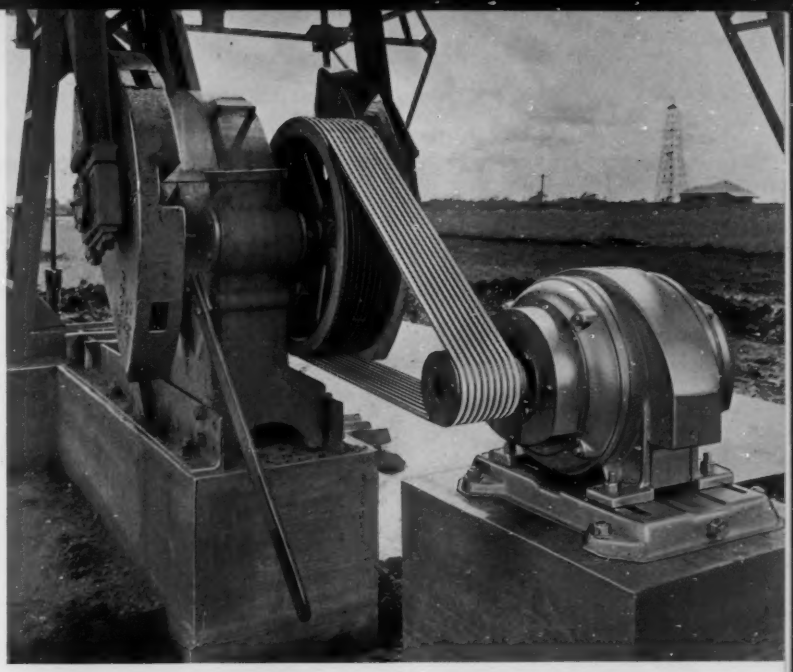
Fig. 5—Two 2000/2800 kw, 500/1000 volt Rectifier Units Recently Installed in Another American Chlorine Caustic Plant

Application of Squirrel Cage Induction Motors

31527

J. M. HILLMAN
Norwood Works
Allis-Chalmers Mfg. Co.



Splash-Proof Motor in Oil Pump Service

THE SUCCESSFUL operation of squirrel cage motor drives depends largely on the choice of a motor having suitable characteristics for a particular application.

Inherently, squirrel cage motors have constant speed characteristics similar to shunt wound, direct-current motors. Certain standards of performance have been established by the National Electrical Manufacturers Association governing torques, starting current, etc., so that practically all the motor manufacturers design to conform to those standards.

The normal starting current, normal torque, cage type motor is recognized in the industry as the standard motor for performance. From this motor the various other types are derived by suitable modification in the design of either the rotor or the stator or both.

The starting torque of the standard cage-type motor varies according to the number of poles, being 150% of full load for 4 pole motors and only 105% for 16 pole motors. Depending on the size, number of poles, and voltage, the starting current varies between 500 and 1000%. This type of motor can be started either on full voltage across-the-line or with reduced voltage starting equipment. Its electrical characteristics and the fact that the motor operates at practically constant speed between no load and full load makes it suitable for almost unlimited application; viz., group drives, blowers, fans, machine tools such as drills, grinders, boring machines, broaching machines, lathes, milling machines, metal saws, shapers, screw machines; centrifugal pumps, metal saws, shapers, screw machines; centrifugal pumps, woodworking machines of almost all types, where normal torque is required for starting the motor.

Normal torque, low starting current motors are recommended for applications where starting currents must be limited either by the requirements of certain power companies or by the generating capacity. This type of motor is designed with high reactance so as to reduce the starting current, making it possible in many cases to connect the motor directly across the line without exceeding the starting current limitations. The performance characteristics, such as torques and efficiency, are comparable with the standard motor and at only a nominal sacrifice in power factor. Motors of this type have the same application as standard motors but enjoy the advantage of lower cost because of the less expensive starting equipment that may be required, as well as the advantage of full voltage starting torque.

A modified type of normal torque, low starting current motor is available for a limited number of applications in sizes above 30 hp in which low starting current is desirable, and where only 50 to 100% starting torque is required, such as for centrifugal pumps, blowers, fans, etc.

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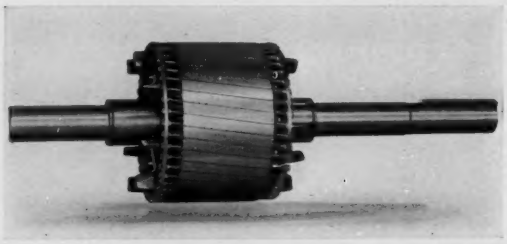

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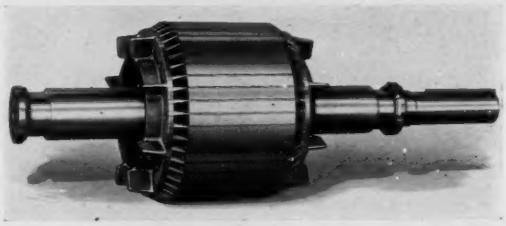
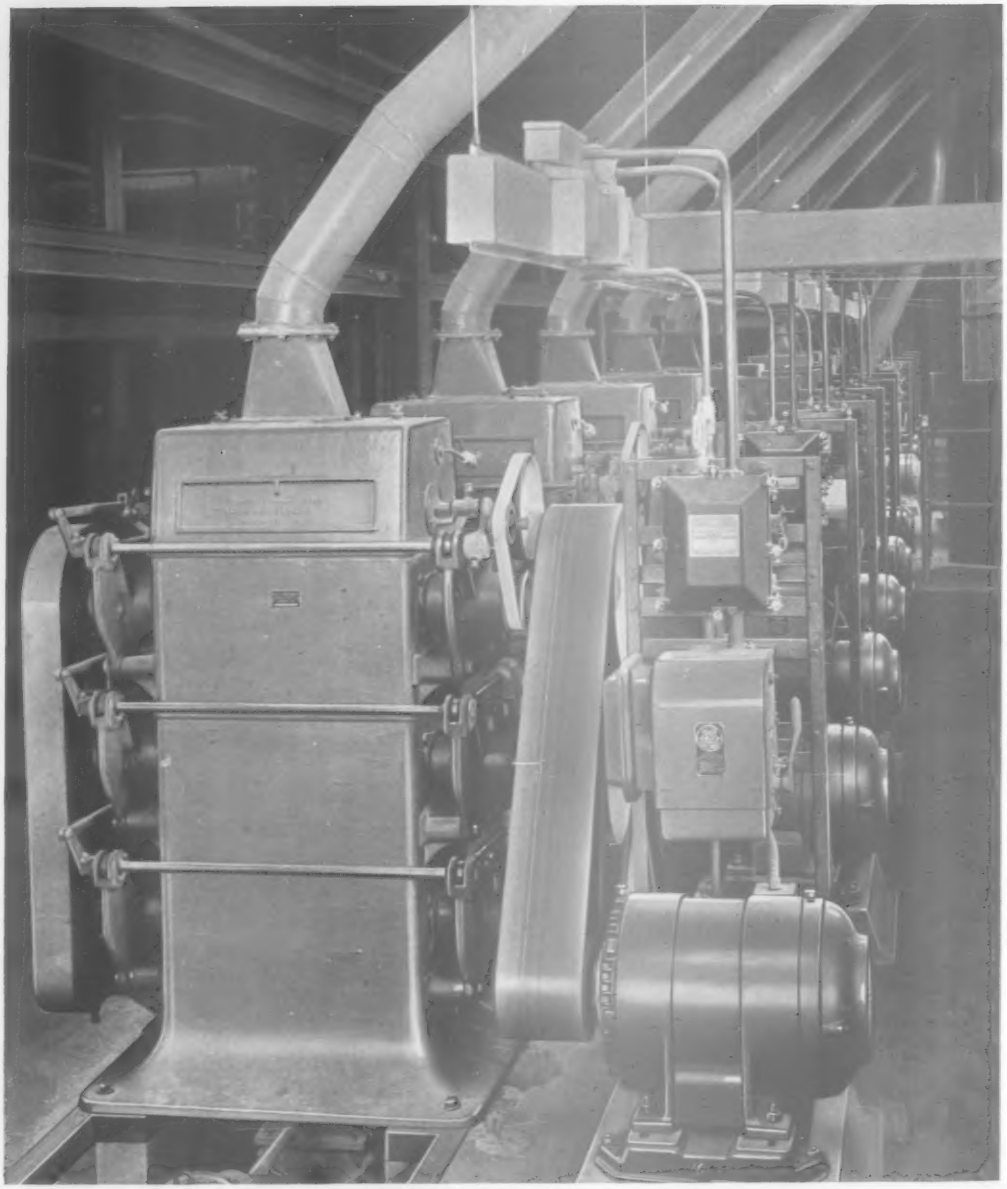


Top—Rotor of Standard Squirrel Cage Motor
Below—Rotor of High Reactance Type Motor



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FAN COOLED MOTORS

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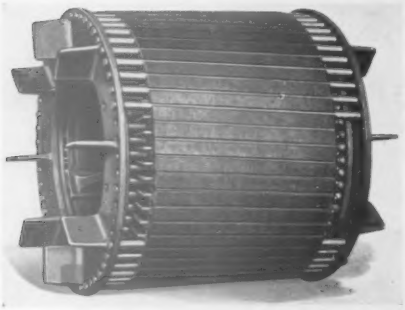

Double Cage Rotor

Double cage, high torque, low starting current motors are applicable for machines requiring higher torque on starting than can be obtained with the normal torque motor and still retain the advantage of low starting current. When started on full voltage, this type of motor produces from 200 to 250% torque.

The efficiency and power factor is somewhat less than is obtained from either of the types described above; however, these disadvantages are offset very largely by the lower overall cost, because the starting current is relatively low and thereby eliminating in many cases current reducing starting devices. The applications are confined to loads which have high inertias and friction to overcome in starting, such as are encountered when driving ball mills, compressors, crushers, and displacement pumps. In this type of motor the higher the torque at starting the lower will be the maximum torque, and conversely, the lower the starting torque the higher the maximum torque.

Machines equipped with fly wheels such as punch presses, shears, and bull dozers, require a motor designed with a high slip in order to provide high starting torque for rapid acceleration. For these applications the proper design of motor permits a reduction in size over the use of either normal torque or high torque with a consequent saving in first cost as well as power consumption.

For cranes, hoists, elevators, and similar loads which require approximately 250% starting torque and whose operation is intermittent, the high torque, high slip should be used. In this type of drive the pullout torque of the motor should not be less than 250% of full load torque with approximately 15% slip in the motor.

It is sometimes desirable to operate machines at more than one constant speed. The multi-speed motor is available for two, three, and four speeds, and with the same electrical modifications as the single speed motor. This group is divided into three classes, briefly as follows:

First, constant torque, in which the hp varies directly with the speed. This type is applicable for driving conveyors, feeders, printing presses, reciprocating pumps, mixers, constant pressure blowers, and other machines of this type.

Second, variable torque, in which the hp output varies as the square of the speed. They are applicable to drives having fan or pump load characteristics.

Third, constant hp, in which the motor must deliver its rated hp at any of the speeds for which it is designed. This condition applies to a great variety of machine tools, as well as classes of wood-working machinery in which the hp requirement is the same at all speeds.

The multi-speed motor is the same in appearance as the single speed motor. It differs, however, in the stator winding employing a single winding or two windings, and by the use of suitable control devices to secure the proper grouping of the poles required to accomplish the desired speed.

In this article consideration has been given only to the electrical characteristics in the application of cage type induction motors. Coupled with this should be the proper selection of a motor with suitable mechanical construction so as to obtain the maximum benefits of minimum cost, low maintenance, and continuity of operation. The final choice as to whether the motor should be sleeve or ball bearing, open, totally-enclosed, splash or drip-proof, fan-cooled, explosion-proof, or, in fact, any of the various types of mechanical construction now available, depends entirely on what local conditions dictate as to the enclosure.

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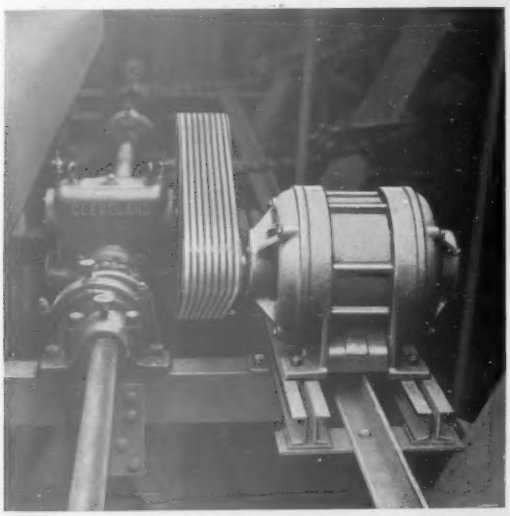

Open Type Motor in Coal Washing Plant

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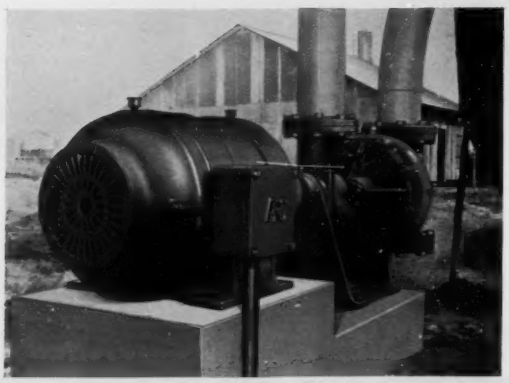


Explosion-Proof Motor Driving Gasoline Pump

Speed Characteristics of Dual Drive Motor Generator Sets

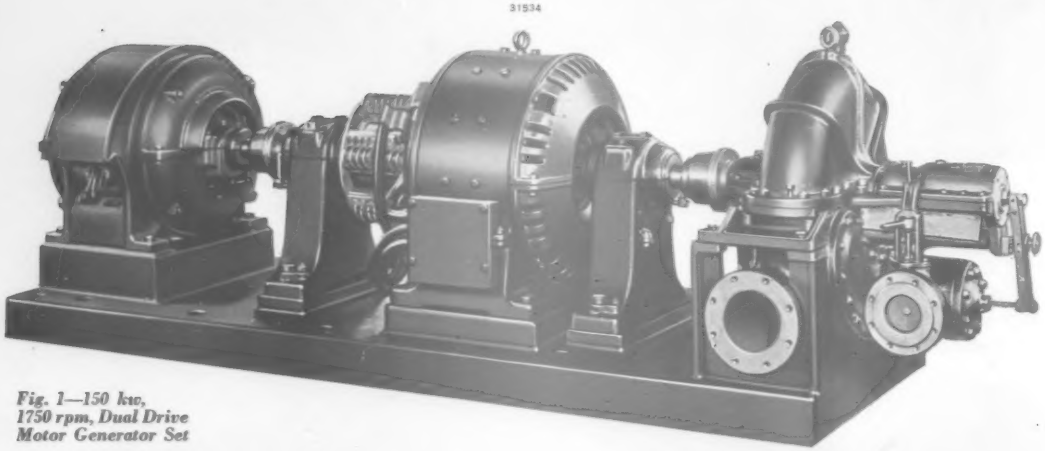


Fig. 1—150 kw, 1750 rpm, Dual Drive Motor Generator Set

C. C. JORDAN
Steam Turbine Department
Allis-Chalmers Mfg. Co.

Solution to Problem of Furnishing Standby Capacity at a Minimum Expenditure

THE DUAL DRIVE motor generator set when properly applied is the ideal solution to the problem of furnishing standby capacity at a minimum expenditure; however, a thorough understanding of the operating characteristics of a dual drive set is necessary to insure proper application.

Fig. 1 shows a 150 kw dual drive motor generator set designed to operate at 1750 rpm. The 150 kw, 125 volt d-c generator is direct connected on one end through a flexible coupling to a standard 250 hp, 2300 volt squirrel cage motor. The opposite end of the generator shaft is direct connected through a flexible coupling to a 150 kw single stage non-condensing steam turbine. On this particular set the turbine was designed for steam conditions of 175 pounds gage pressure and 100° F superheat at the throttle and five pounds gage exhaust pressure.

The speed governing system on the steam turbine illustrated consists of a centrifugal governor mounted directly on the turbine shaft, a steam regulating valve and suitable levers connecting the shaft governor extension to the steam regulating valve stem. Hand adjustment of the speed is provided by a speed changer consisting of a fulcrum block which is movable by means of a hand operated screw. This type of governing system, known as direct operated with shaft governor, carries a speed regulation guarantee of 8% speed change from no load to full load.

Where desired, an oil relay type governing system can be furnished which carries a speed regulation guarantee of 4% speed change from no load to full load; however, turbine driven for dual drive motor generator sets are seldom fitted with the oil relay type governor due to the considerably greater initial cost.

In order to better understand the operation of the direct operated governing system, it is well to consider

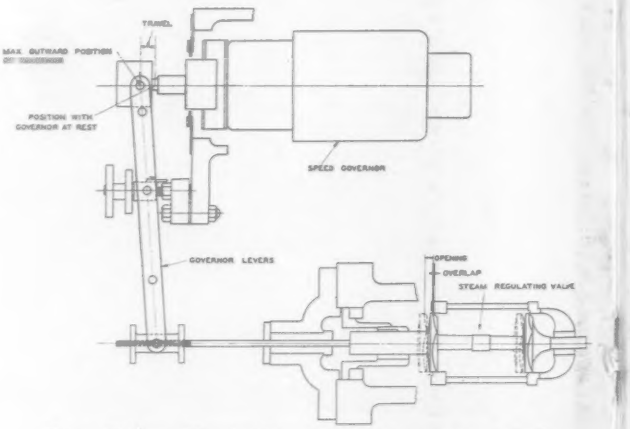


Fig. 2—Diagram Showing Direct Operated Governing System

the diagram shown in Fig. 2. As shown, the stem regulating valve is of the double-seat disc-type sliding inside of a valve cage. For closed position the valve overlaps the valve cage $\frac{1}{8}$ inch. Obviously, this is necessary since a certain amount of overtravel must be provided to close the valve but prevent it from jamming when the set is being operated from the motor. The governor levers are designed so that the $\frac{3}{4}$ inch governor travel represents the full valve travel plus the $\frac{1}{8}$ inch overlap. The governor is ordinarily set so that the steam regulating valve will start to open at a speed slightly less than the full load speed of the set when operating from the motor drive. This will insure negligible steam consumption of the turbine when using the motor drive.

When the turbine governor is properly set and the dual drive set started by the motor, the turbine throttle is opened. The speed at which the turbine governor is being operated by the motor holds the steam regulating valve in the overlap position, thus preventing all steam admission to the turbine except that which leaks through the clearance space between the valve and the cage. This leakage is sufficient to keep the turbine blading from overheating. If the motor should fail, the drop in speed would open the steam regulating valve to permit the turbine taking over the load.

Fig. 3 shows graphically the speed regulation characteristics obtained on test of the dual drive set illustrated by Fig. 1. When driven by the motor, the speed of the set dropped from 1785 rpm at no load to approximately 1765 rpm at full load. When driven by the turbine, the speed of the set dropped from 1760 rpm at no load to 1700 rpm at full load. This speed change on the turbine drive represents a speed regulation of approximately 3½%, which is extremely good when the 8% guarantee is considered.

When the curves in Fig. 3 are studied, it is evident that the turbine steam regulating valve is closed over the full load range on the generator when the set is being driven by the motor, since the full load speed of the set on the motor is 5 rpm higher than the no load speed on the turbine. The entire speed curve on the turbine could be raised by the speed changer, thus raising the full load speed of the set when operating on the turbine. If the turbine speed is raised 15 rpm

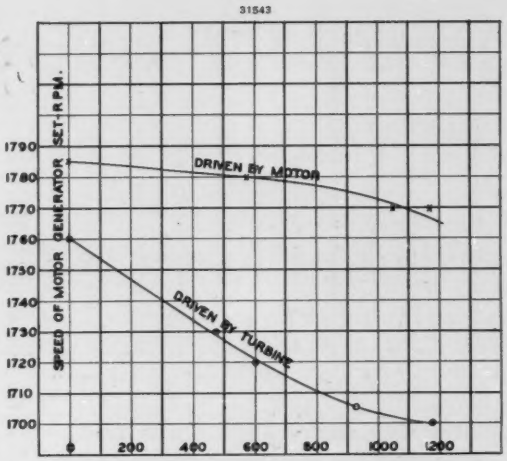
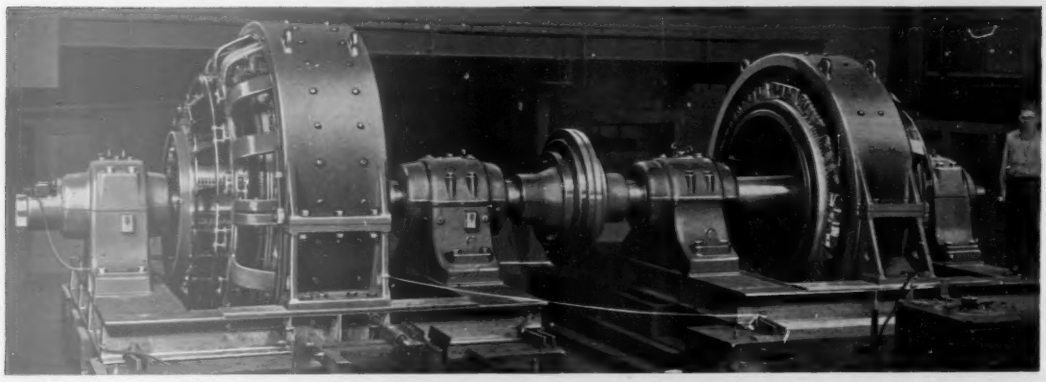


Fig. 3—Speed Regulation Characteristics of Dual Drive Set

to give a full load speed of 1715 rpm, the speed at which the turbine would start carrying load would also be raised a like amount. When the set is operating on the motor drive, the turbine would start to carry some load when the generator load increases to approximately 900 amperes.

The dual drive arrangement furnishes a means of driving the generator under ordinary conditions, by a motor, with the additional insurance of having a turbine drive to automatically pick up the load if the motor fails. From the above discussion, however, it is evident that there must be a drop in speed to cause the turbine to pick up this load and that, for economy in steam consumption when the set is being driven by the motor, this drop in speed should start at about the full load motor speed.



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Buck and Boost Test Set-up for Large Hot Finishing Mill Motors. Left—3500 hp, 175/350 rpm, 600 volt. Right—2500 hp, 225/450 rpm

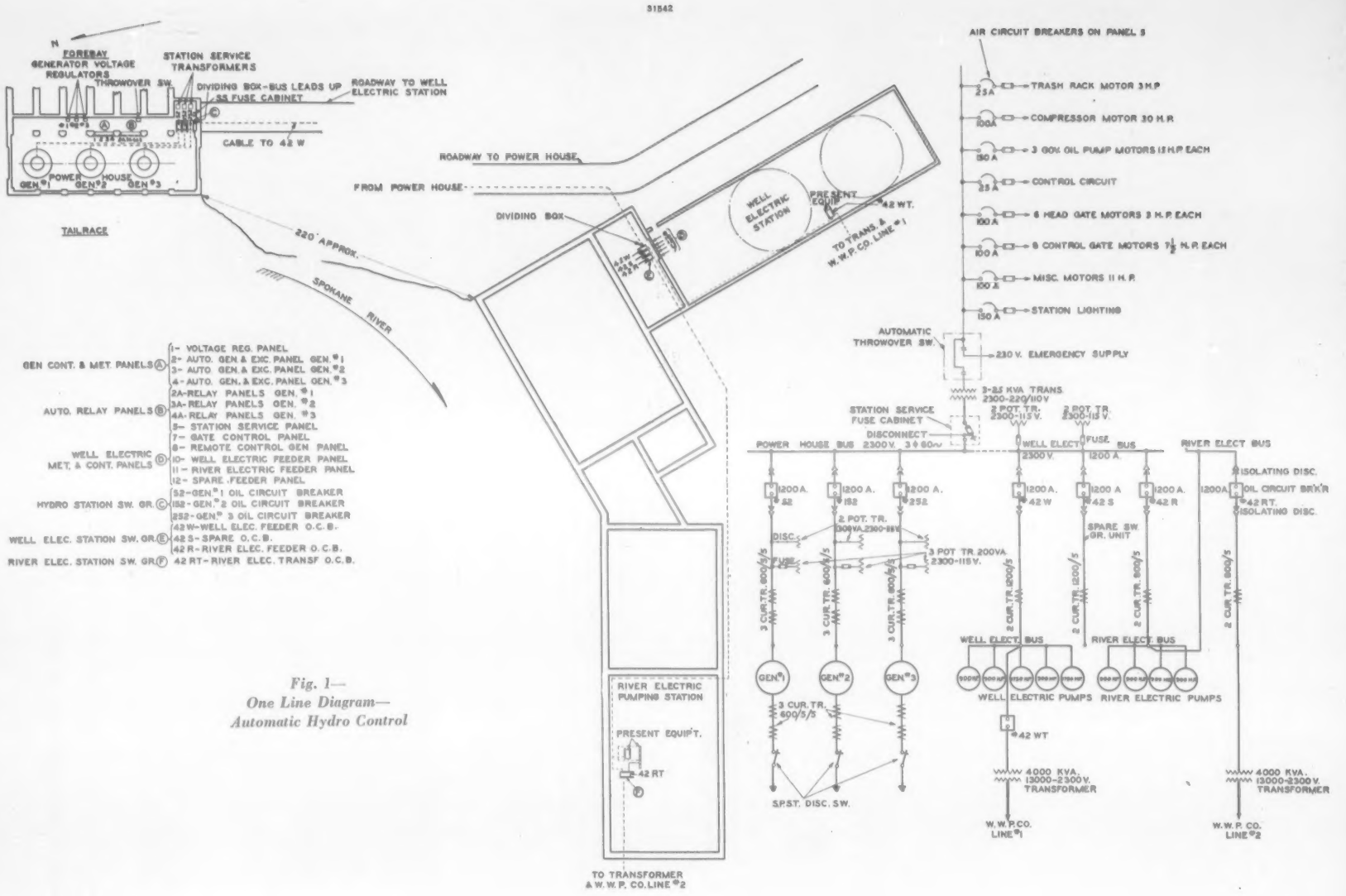

Fig. 1—
One Line Diagram—
Automatic Hydro Control

Automatic Hydro Control

An Example of Its Adaptability to Specific Requirements

T. B. MONTGOMERY
Control Engineer, Switchgear Division
Allis-Chalmers Mfg. Co.

IN A LAND where a major part of the year snow clad peaks look out on fertile valleys and vast tracts of mechanized agriculture stretch before the eyes, the crystal clear waters of the Spokane River pass through the center of the so-called capital of this "Inland Empire."

The water supply for the Spokane Metropolitan area of some 125,000 people is obtained from wells located on the river banks about six miles above the city.

The pumping station consists of three sections or bays, installed at different periods. The latest bay installed some twelve years ago consists of synchronous motor driven centrifugal pumps. The next bay of induction motor driven double unit centrifugal pumps was installed some twenty-two years ago and the power for these bays has previously been purchased. The original section, which consists of three batteries of reciprocating pumps each geared to a line shaft driven from a vertical hydraulic turbine through wooden bevel gears, has been in continuous operation for forty-two years.

Under the present program, the reciprocating pumps and turbines are being removed and a completely modern hydro-electric plant installed 400 feet upstream from the station. The water which is diverted through a canal will now pass directly into the turbine intakes and will discharge into the river bed. Power will be supplied directly to the pumping station bus at 2300 volts, 3 phase, 60 cycles.

The turbines are of the latest medium head type, with a high speed propeller. The automatic speed governor adjusts the guide vanes, thereby controlling the flow of water through the turbine before it enters the propeller runner, which has five pivoted blades, also automatically adjusted by the governor for the purpose of obtaining the highest possible efficiencies at all conditions of load and operating head.

The propeller blades are jointly operated inside of the rotating hub by a shaft and piston located in an enlargement of the turbine shaft at its upper end which forms the oil operating cylinder. This enlargement has a flange for bolting directly to the generator shaft flange. The oil acting under pressure upon this piston is admitted from the top of the generator through piping inside of the generator shaft, and the movement of this piston is relayed back to the governor, so that a fixed inter-relation exists at all times between guide vane opening and propeller blade tilt.

Each unit is rated 2300 hp maximum under 32 feet net head, the propeller having a maximum diameter of about 86 inches.

The automatic control for these units represents the latest development and is a typical example of the adaptability of automatic control to special requirements showing the advantages of coordinating the design of turbines, generators and control.

The output of the three 1625 kva, 2300 volt, 3 phase, 60 cycle, 80% power factor hydro-units will be used entirely to drive the pumping plant, but in order to obtain the maximum in reliability the two separate sources of purchased power will be retained for emergency use and to supplement the station at times of low power output.

Since the control problem involved not only the hydro-station but the supervision and power feed to the two motor driven bays of the pumping station from three different power sources, a point in the Well Electric Station shown at D in Fig. 1 was selected as the central control point.

Furthermore, the two sources of purchased power (Line No. 1 and Line No. 2) cannot be paralleled, and as an added condition it is not desirable to parallel Line No. 2 with the hydro-station. The condition then is one of having two sections of a pumping station, with provisions for a third, normally driven from an automatic hydro-station with Line No. 1 arranged to supply one or both sections on demand either singly or in parallel with the hydro-station and Line No. 2 to supply one or both sections individually.

Hydro-Station Control

The steps required to automatically start and stop a water wheel generating unit have become standardized to a considerable degree. The control methods vary slightly as do the number of protective devices required by different purchasers. However, special features of each installation require some operating characteristics which are individual, as in this case:

a. Start and stop each hydro-unit automatically by remote control either from the hydro-station or the Well Electric central control board.

b. Synchronize manually when desired at either point.

c. Operate head gates and indicate head gate position from the Well Electric Station.

d. Indicate loads, voltage, etc., at both points.

Such characteristics prevent complete standardization of automatic control and require that each installation be specially engineered.

The generators are connected to the line by the synchro-operator, which has been described elsewhere. This instrument acts automatically to match the frequency of the incoming generator with the bus frequency and close the breaker at the proper time. It also gives visual indication of phase angles. If, however, a unit is started with the bus "dead" the generator breaker is closed at approximately 80% voltage.

As an added feature after connection, the governor setting is automatically raised a definite amount causing the unit to assume load.

Protective operations are divided into two groups, namely:

1. Shut down or prevent starting until correct conditions obtained due to abnormal conditions of temporary nature.
   a. Prevent starting if the machine has been shut down by a lockout protective device.

b. Prevent opening of the generator oil circuit breaker on normal shutdown or on transient low a-c voltage until the water wheel gates are closed to the no load point.

c. Prevent the generator being reconnected without going through the normal sequence of starting or synchronizing if for any reason the breaker is opened.

d. Shut down the machine when the stopping indication is given by the master element control switch.

Shut down the machine temporarily in case of occurrence of any of the following conditions after the correction of which the machine may be restarted:

(No. 12) e. Overspeed—on return to 80% speed the machine may restart.

(No. 49) f. Moderate overload sufficient if continued to overheat generator windings.

(No. 63) g. Failure of governor oil pressure.

h. Excessive exciter overvoltage.

2. Shut down and "lockout" the machine on occurrence of any of the following conditions:

(No. 46) i. Unbalanced phases sufficient to overheat the generator windings.

(No. 38) j. Overheated bearings.

(No. 40) k. Failure of excitation.

(No. 59) l. A-C overvoltage.

(No. 87) m. Failure of machine windings.

(No. 51) n. A-C heavy overload or shortcircuit.

o. Failure to synchronize or to complete the starting sequence.

p. Failure to build up voltage in starting.

q. Failure of circulating water to the turbine bearing.

A lamp annunciator system is provided on the generator panel with individual indicating lamps for each protective operation, except governor oil pressure failure and overspeed, so that upon occurrence of an abnormal condition a corresponding lamp marked by a nameplate will be lighted showing the operator at a glance the nature of the trouble.

These lamps are extinguished by operating the reset switch on the generator panel after the operator has made an inspection.

Arrangement

It is in the location of the apparatus to suit the layout which make the individual characteristics of this installation stand out. As shown at the top left of Fig. 1, the control apparatus is divided physically into six groups:

(A) Generator control and metering panels.

(B) Generator field and relay panels.

(C) Hydro-station switchgear.

(D) Well Electric metering and control panels.

(E) Well Electric Station switchgear.

(F) River Electric Station switchgear.

The last two items are generally separated from the rest of the equipment.

On the upstream side of the power house a row of pilasters extends the length of the building midway between the generators and the upstream wall. The hydro station control is divided into two sections, A and B, as shown, each of which are adjacently mounted between two pilasters and completely filling the available space. Grillwork fills the space between the other pilasters resulting in a uniform appearance rather than the usual irregular appearance.

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Fig. 2—Generator Control and Metering Panels

Fig. 2 shows the generator control and metering panels consisting of three duplicate generator panels each mounting meters, protective relays, a lamp annunciator, manual control switches and switches for transferring from local to remote control from the Well Electric Station and from automatic to manual control. At the left of this group of panels is the voltage regulator panel mounting the control elements, transfer switches, and adjusting rheostats for three rocking contact type rheostatic voltage regulators which maintain constant generator voltage under various load conditions. These regulators are of the high speed type and are connected in the exciter fields. The regulator control elements act on the rheostats, mounted behind and to the left of the control board A, Fig. 1. On the

31530

Fig. 3—Three Duplicate Generator Field and Relay Panels With Station Service Panel at Right

rheostats are mounted the high speed contactors. The control elements are equipped with two sets of contacts. On small load changes requiring slight movement of the rheostat for correction, the first set of contacts operates the rheostat until correct voltage is obtained at the point where the regulator comes to rest. On large load changes or voltage fluctuations, both sets of contacts come into play, and the high speed contacts act to maintain substantially constant voltage until the rheostat has made the required travel to reach the new setting where the regulator again comes to rest. The synchro-operator is mounted on the center generator panel.

Fig. 3 shows three duplicate generator field and relay panels mounting field contactors, timing relays and auxiliary relays which control the various steps in starting and stopping the units. To the right of these panels is the station service panel. To the right of and behind this panel is mounted a throw-over panel which automatically transfers the station auxiliaries to an emergency source in case of power failure and transfers back again on power restoration. All panels in the hydro-station are of ebony asbestos.

Referring again to Fig. 1, the hydro-station switchgear is located at the south side of the building between the last pilaster and the wall. These units are of the armor-clad type, 100,000 kva interrupting capacity, with bus and all live parts completely embedded in compound. The instrument transformers are also encased in chambers filled with soft removable compound for ready access in case changes are required.

Fig. 4 shows the Well Electric central control board, which is of steel. Here again the appearance is kept uniform by inserting this board in an opening in the wall at the north end of the Well Electric control gallery.

The panel at the left is the head gate remote control and indicating panel. The next three panels are feeder panels for the pumping station, and the panel at the right is the generator remote control panel.

Directly behind this control board, in the older part of the building, is located the Well Electric Station switchgear, which is of the latest design armor-clad type including the expulsion port principle of arc extinction. This gear is similar in all respects to the hydro-station switchgear.

The River Electric Station switchgear consists of a single unit similar to the others except it is controlled from the River Electric Station control panels.

Power Control From Feeders

The station feeders from the three power sources are controlled from breaker control switches on the Well Electric central control board. In order to use these sources to the best advantage, the following operating combinations, referring to Fig. 1, have been set up and adequate interlocks provided so as to make all operations fool-proof:

1. Feed power from W. W. P. Co. Line No. 1 through feeder breaker 42 WT to the Well Electric bus only.
   a. 42 WT cannot be closed unless 42 W is open.

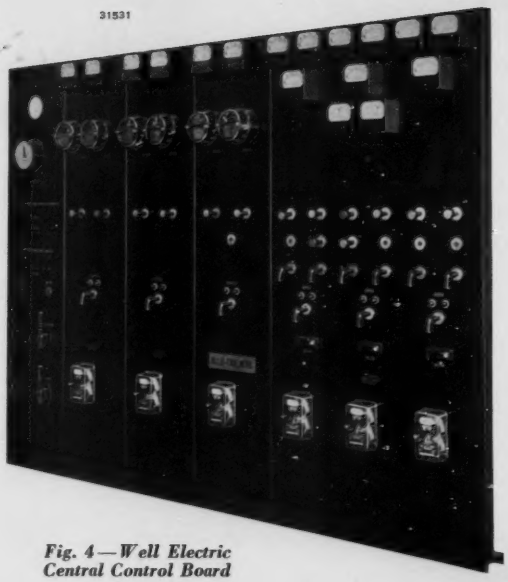
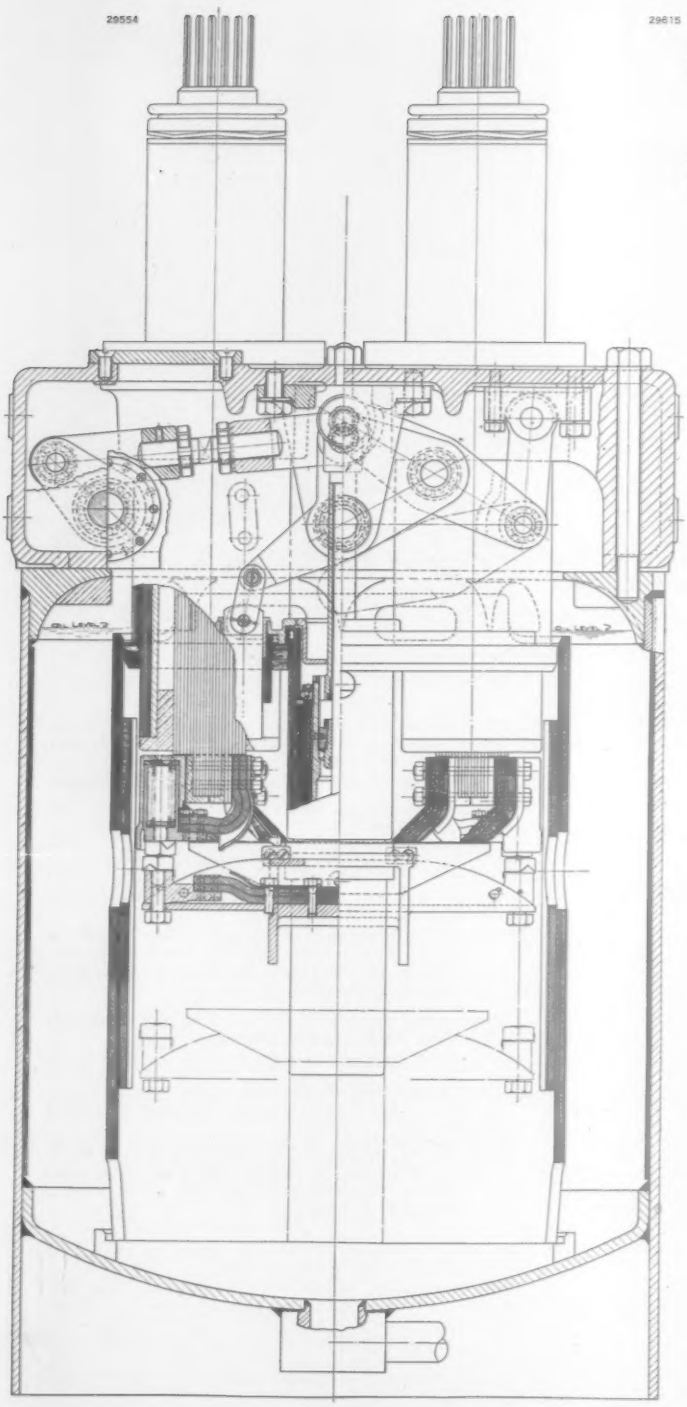
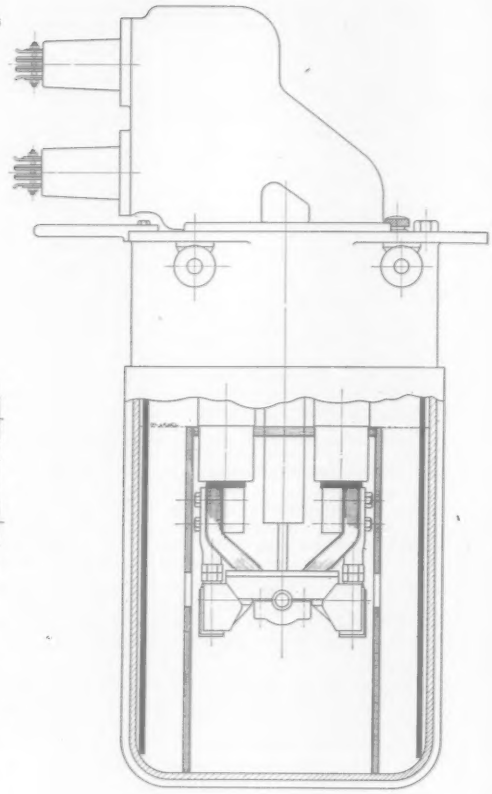


Fig. 4—Well Electric Central Control Board

2. Feed power from W. W. P. Co. Line No. 1 through feeder breaker 42 WT to the Well Electric bus and the River Electric bus.
   a. 42 WT cannot be closed unless 42 W is open.
   b. 42 W cannot be closed unless the synchronizing switch is closed or all three generator breakers are open and 42 R or 42 RT is open.
   c. 42 R cannot be closed unless 42 RT is open.
3. Synchronize generator bus with W. W. P. Co. Line No. 1.
   a. 42 WT cannot be closed unless 42 W is open. 42 W cannot then be closed unless the synchronizing switch is in the position connecting the synchroscope.
4. Feed power from W. W. P. Co. Line No. 2 through 42 RT to the River Electric bus.
   a. 42 RT cannot be closed unless 42 R is open.
5. Feed power from W. W. P. Co. Line No. 2 through 42 RT to the River Electric bus and the Well Electric bus.
   a. 42 RT cannot be closed unless 42 R is open.
   b. 42 R cannot be closed unless all three generator breakers are open and either 42 RT or 42 W is open.





The Expulsion Port Circuit Breaker—

The sectional view above illustrates the construction used on these breakers. The difference between expulsion port breakers and breakers without expulsion ports can clearly be seen.

Left — Construction of an expulsion port breaker of the 3-pole, 3-tank type, built for a rating of 4,000 amperes, 23,000 volts and having an interrupting capacity of 2,500,000 kva, at the operating voltage of 16,500 volts.

EXPULSION PORT OIL CIRCUIT BREAKERS

Arc Extinguishing Principle Makes These Breakers Extremely Efficient as Circuit Interrupting Devices

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Engineer-in-Charge
Switchgear Division
Allis-Chalmers Mfg. Co.

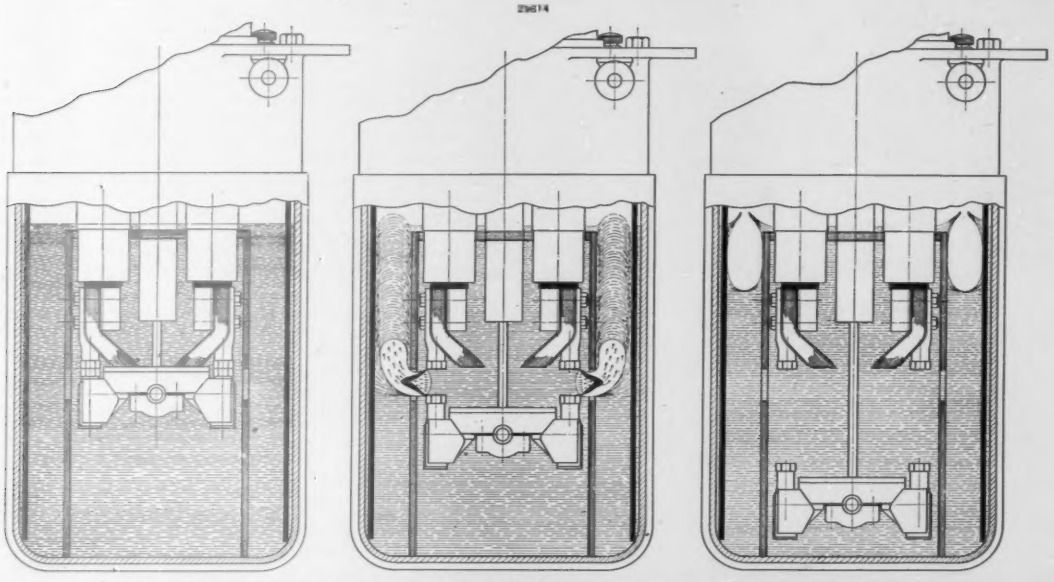
ALTHOUGH the fundamental principle underlying the design of an oil circuit breaker must be the same if efficient arc interruption is to be obtained, it is nevertheless surprising how different in mechanical construction arc interrupting devices can be developed which are still very efficient devices for the purpose intended. The individual ruptor* applied to each pole lends itself admirably to breakers of moderately high voltage and particularly to breakers having a separate tank for each phase.

In the lower voltage classes of breaker, however, and particularly in the smaller breakers at 15,000 volts, the space requirements become such that the individual enclosure around each breaker contact becomes an increasingly greater design problem. As the voltage is reduced the problem of handling greater and greater currents grows and there is greater necessity for so designing the breaker that they can be applied on much lower voltages than their rating to handle correspondingly higher currents. The expulsion port breaker has been developed as a result of several years of testing and experimental work. This type of breaker although not differing greatly in mechanical construction from breakers which were built heretofore has incorporated in it an arc extinguishing principle which makes these breakers extremely efficient as circuit interrupting devices.

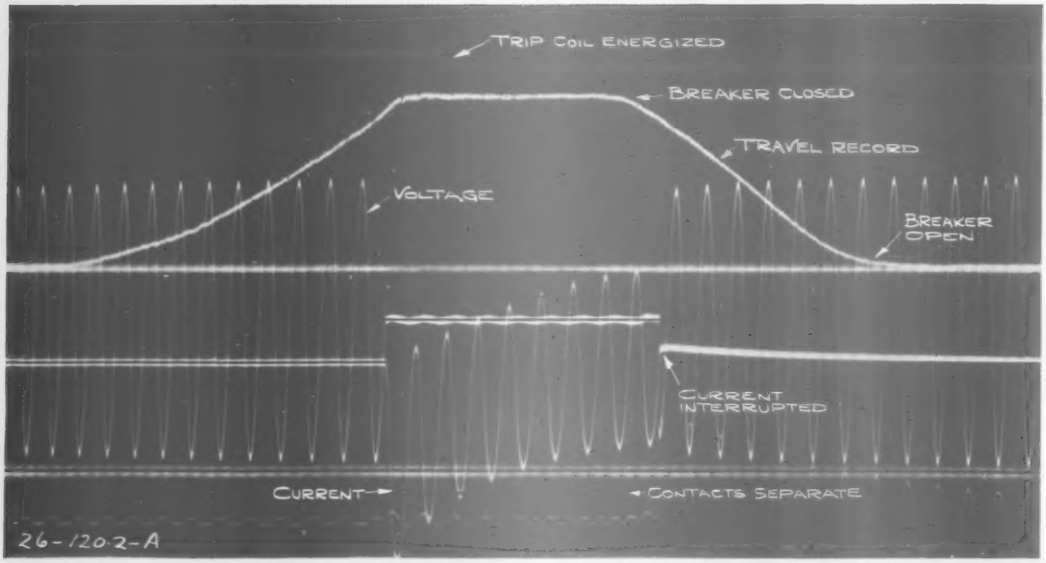
*See Allis-Chalmers Electrical Review, September, 1936.

The fundamental principle of the expulsion port breaker is that of drawing an arc in a closed oil chamber with the only point of egress for the gases formed by the arc being an opening or port located adjacent to the point of arcing. Under these conditions, as soon as an arc is struck, gas is formed which passing out through the port at high velocity, results in a blast action and turbulence at the point of arcing which tends to disrupt the arc stream and shut off the conducting path during the zero point of the current wave.

In the construction of the expulsion port breaker for armorclad switchgear up to capacities of 500,000 kva, and 15,000 volts, all the simplicity of contact arrangements and the accessibility of contact parts that has been one of the good features of the plain break breakers heretofore built have been retained. Neither does



Left to Right—Expulsion Port Oil Circuit Breaker Closed, Interrupting and Open



29816 *Typical Oscillogram of Short-Circuit Test on Expulsion Port Oil Circuit Breaker*

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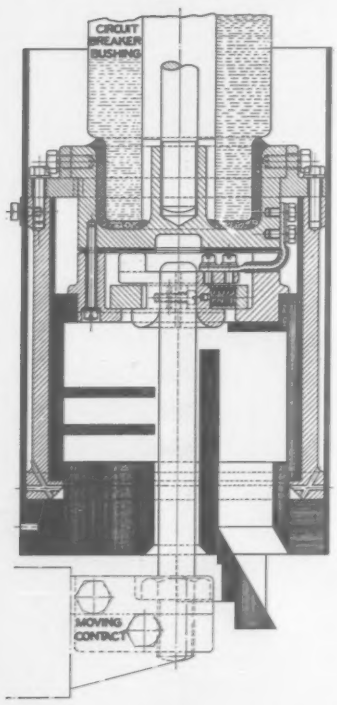


Sectional View of Expulsion Port Contact for 34.5 kv Breaker

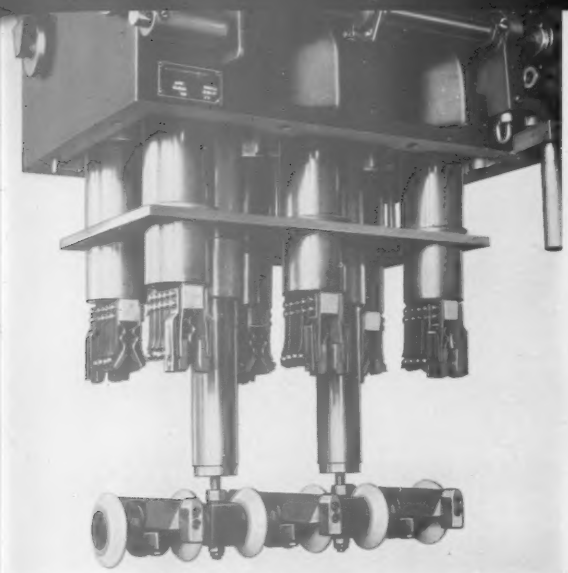
the design hamper the use of arcing contacts of sufficient mass and ruggedness required to close in and handle heavy short circuits, even when these breakers are applied on much lower voltages than their rated voltage.

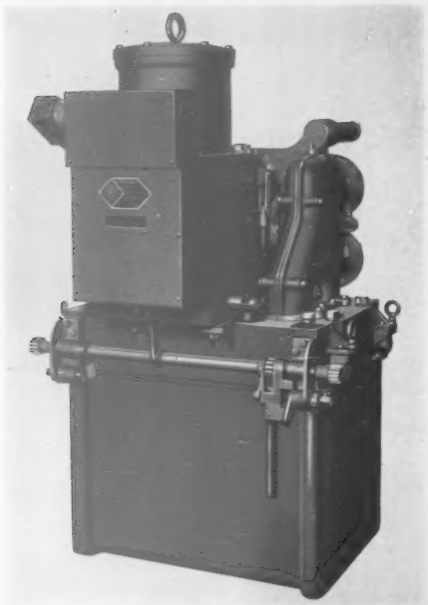
The circuit breaker tank is provided with a special liner, which carries a barrier which, when the tank is in place, nests with a horizontal barrier across the circuit breaker bushings, forming a central oil chamber in which the contacts are placed and which has no opening by which gases can reach the air cushion above the oil except through the expulsion port openings adjacent to the arcing contacts. This results in a symmetrical construction which gives two efficient breakers per phase, each opposite its own expulsion port and which independently operate to extinguish the arc and expel the generated gases out through the adjacent port.

When we get into the larger breakers, a distinct division arises between breakers of 23 kv, and below which must be designed to withstand extremely heavy short-circuit currents with their resulting magnetic stresses, and breakers of 34 kv, and above where the actual short circuit currents are comparatively small.

The large sectional view on page 26 shows the construction of an expulsion port breaker built for a rating of 4000 amp and 23,000 volts having an interrupting capacity of 2,500,000 kva. This is a three tank breaker and the view shows the section of one pole only.

It will be noted that in this breaker in order to handle the enormous short-circuit currents involved at the service voltage, a massive construction of contacts has been used which assures not only a low operating temperature under the rated load of the breaker, but also adequate mass of arcing contact material to handle the short-circuit currents without welding or rapid deterioration of contacts. Such a rugged arrangement of the contact parts would not have been possible with any other type of arc extinguishing means. This being a three tank breaker, each pole in an individual tank, the tank is, of course circular and the barrier which





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surrounds the contacts parts can therefore, be made in the form of a cylindrical tube. This tube is carried by the tank so that when the tank is lowered, the contacts are open and accessible for inspection without the removal of any other parts.

When it comes to the higher voltage breakers, the problem of handling the short-circuit currents is nowhere near so difficult, and owing to the increased spacing required by the voltage involved, it becomes more economical to build an expulsion port device for each arcing contact. On page 28 is a sectional view showing the construction of the expulsion port contact as applied to a 34.5 kv 1,500,000 kva breaker. It will be seen that although the principle of arc extinction is exactly the same as in the lower voltage breakers illustrated, the mechanical arrangement of the breaker is quite different.

In order that a clear understanding may be had of the constructional features of these breakers, several pictures of actual breakers, showing the contact and barrier construction and also a typical oscillogram taken cn one of these breakers under short-circuit test, are shown.

The advantages obtained in the expulsion port breaker by this improved construction, and more efficient arc interrupting means compared to previous types of breaker may be summarized as follows:

1. Arc interruption is accomplished much easier and with lower internal pressures and consequently the factor of safety of the breaker is greatly increased.
2. These breakers are oil tight and do not throw any oil under service conditions.
3. The oil deterioration and contact deterioration is enormously less than in a plain break breaker which means that the maintenance required by these breakers is very much less than previously necessary.
4. The arcing time is materially shorter and consequently the short-circuit interruption is attained quicker.
5. These breakers are not sensitive to variations in current value and therefore are efficient as arc interruptors through a wide range of current. This enables the breaker to be applied on various service voltages with the assurance of the same interrupting performance as at the rated voltage.

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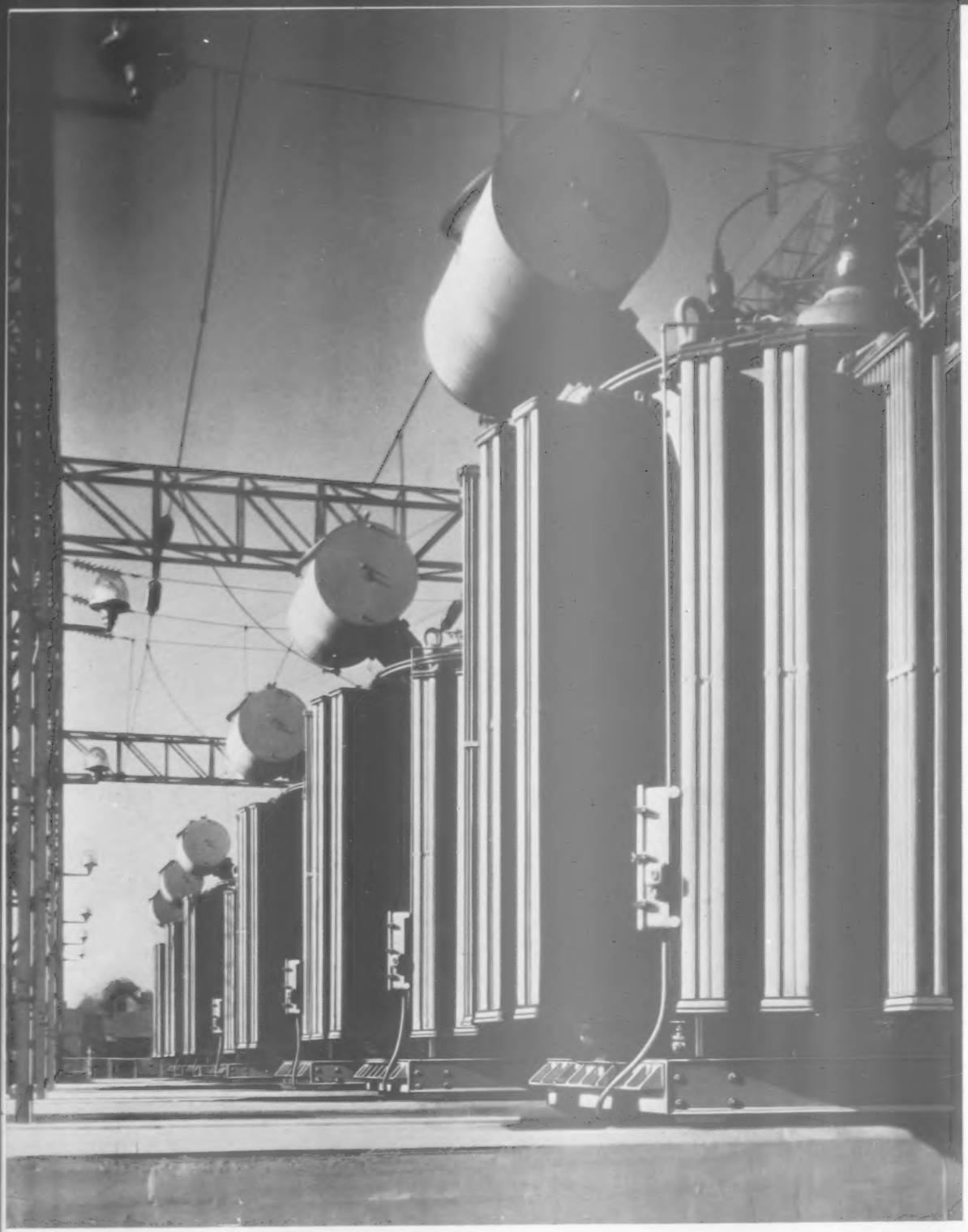
From Top to Bottom—

Type C Expulsion Port Breaker, 600-amp, 15,000 volts

Type B Expulsion Port Breaker

Type C Circuit Breaker Tank Showing Expulsion Ports and Barriers

Type B Circuit Breaker Tank With Expulsion Ports



Power Transformers

Service Gaps for Transformer Bushings

F. W. BUSH
Transformer Division
Allis-Chalmers Mfg. Co.

THERE IS an increasing tendency to consider a transformer adequately protected against lightning if it is equipped with bushing gaps set equal to the recommended test gap settings. Unfortunately, this is not true, and the characteristics of the rod gap under impulse conditions should be thoroughly understood before it is depended upon for lightning protection.

The A. I. E. E. Transformer Subcommittee has set up a list of rod gap settings called "test gaps," which represent the coordination levels for the various voltage classes. These levels, however, are based on the minimum impulse flashover of the various rod gaps when tested with a 1½-40 microsecond positive wave, and the transformer insulation strength is designed to be somewhat stronger than the respective levels.

Unfortunately, the rod gap possesses a time lag characteristic whereby it will allow higher and higher voltages for shorter and shorter times. Fig. 1 shows the volt-time characteristics of various rod gaps when tested with the 1½-40 positive wave. The minimum flashover of the test gap will occur in from five to twenty microseconds depending on the gap length. If, however, a voltage wave of higher magnitude or steeper wave front is applied to the gap, the gap will flashover at a considerably higher voltage but in a shorter time. Because of this "time lag" effect, a transformer may be subjected to voltages much higher than the normal test level if it is protected only by the standard test gap. Accordingly, where gaps are to be used for protection, the gap setting must be considerably reduced below the A. I. E. E. test figure.

From the standpoint of transformer protection, the smaller the gap the better the protection. The practical limit, however, is the smallest gap which will not give too many outages due to switching surges, arcing grounds and normal frequency over-voltages. Previous investigations* have shown that if the 60-cycle flashover of the protective gap is at least four times normal line to neutral voltage, there will be little probability of outages due to switching surges and arcing grounds. With this as a basis of calculation, Table I shows the various minimum gaps which may be applied to the various circuits. It will be noted that in the higher voltage classes, the calculated gaps are quite consistent and are just about equal to 75% of the standard test gaps. In the lower voltage classes, the calculated gaps are quite low when compared to the test gap. Experience to date has indicated that bushing gap settings of 50% of the normal test gap for circuit voltages up to 13.8 kv and 75% of the normal test gap above 13.8 kv are desirable.

The use of these reduced gap settings will materially increase the protection of the transformer, but it should be remembered that even where they are used, the transformer is not entirely protected against very steep voltage waves such as may occur on direct hits in close proximity to the transformer.

TABLE I

Circuit Kv	*Length of Test Gap Inches*	*Assumed Maximum Switching Surge Kv*[1]	*Calculated Minimum Bushing Gap Inches*[2]	*Minimum Bushing Gap in % of Test Gap*	*Proposed Bushing Gap in % of Test Gap*
1.04	.8	2.4	.12	15.0	50
4.33	2.2	10.0	.5	22.7	50
8.66	3.3	20.0	1.1	33.3	50
13.8	4.5	31.9	2.0	44.4	50
22	7.1	50.8	3.8	53.5	75
33	10.2	76.2	6.5	63.8	75
44	13.5	101.5	9.7	71.8	75
66	20.6	152.5	15.2	73.7	75
88	27.5	203.0	20.5	74.5	75
110	34.7	254.0	25.8	74.2	75
132	42.1	305.0	31.2	74.0	75
154	49.0	356.0	36.5	74.5	75
187	60.0	432.0	44.0	73.4	75
220	70.4	508.0	52.0	74.0	75
275	88.0	635.0	66.0	75.0	75
330	105.6	762.0	81.0	76.7	75

[1]Maximum Switching Surge = 4 × (60 cycle Line to Neutral Voltage). See A. I. E. E. Paper No. 33-39, "Coordination of Insulation," by Montsinger, Lloyd and Clem, 1933, for data concerning switching surges.
[2]The Minimum Bushing Gap length is taken as the gap which has the same 60-cycle flashover as the Maximum Switching Surge.

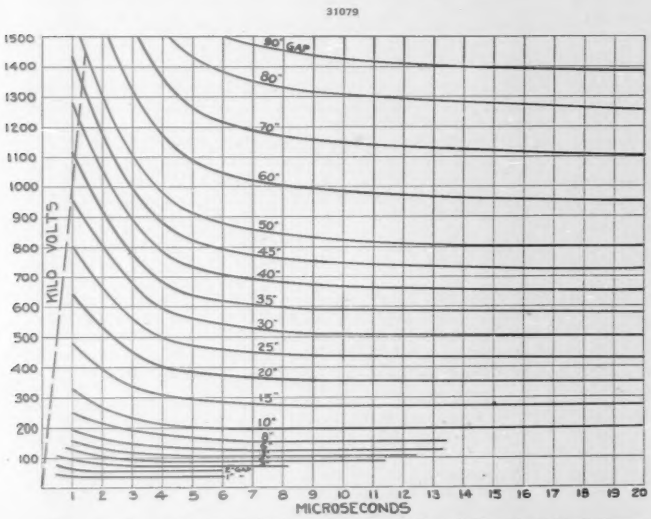


Fig. 1—Approximate Volt-time Characteristics of Standard Rod Gaps. 1½-40 Positive Wave

*NEMA Paper No. 33-39, "Coordination of Insulation," by Montsinger, Lloyd and Clem, 1933.

SYMMETRICAL COMPONENTS SIMPLIFIED

The Solution of Unbalanced Three Phase Electrical Circuits by Resolving Them Into Balanced Components

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General Principles

WHEN 3-phase circuits are balanced, the determination of the voltage and current relations is relatively simple. When the voltages, currents or impedances are unbalanced, the solution becomes more complex, particularly when there is mutual inductance between various parts of the circuit.

If by some method an unbalanced circuit can be represented by a combination of several balanced circuits, each balanced circuit can be solved independently without difficulty, and the several solutions can be combined to give the complete solution.

Such a method is available in what is commonly called "symmetrical components." To use the principle of symmetrical components, an unbalanced 3-phase system is replaced by three balanced 3-phase systems. The relations existing in each one of these systems can be determined in the usual way for a balanced 3-phase system. The three separate solutions thus obtained can be combined to give the actual conditions of voltage and current.

General Method of Resolution

To resolve a 3-phase system of currents into its symmetrical components, each current is represented by three other currents; the vector sum of these three other currents is equal to the actual current. The three actual currents are represented, therefore, by a total of nine currents. If the components into which each current is divided are properly chosen, the nine resultant currents can be grouped into three balanced systems. Assume, for example, that the three original currents are A, B and C, respectively, and that they are properly resolved, as follows:

Current A resolved into currents A_0, A_1 and A_2
Current B resolved into currents B_0, B_1 and B_2
Current C resolved into currents C_0, C_1 and C_2

Then the nine resultant currents can be grouped into three balanced systems:

First, A_0, B_0 and C_0
Second, A_1, B_1 and C_1
Third, A_2, B_2 and C_2

The proper division of each current into components may be accomplished without difficulty by substitution in proper formulae, which will be given later.

The first of the three balanced systems consists of three currents equal in magnitude and in phase with each other. This system is commonly called the zero sequence system, because the currents are zero degrees apart in phase. The zero sequence currents in a 3-phase system are equal; that is, each of the three phase lines carries the same current in the same direction. This current must return through the neutral which will have the sum of the three currents flowing in it. The three zero sequence currents are equal to

$$A_0 = B_0 = C_0.$$

The current in the neutral is

$$A_0 + B_0 + C_0 = 3A_0 = 3B_0 = 3C_0.$$

The second of the three balanced systems consists of three currents equal in magnitude but displaced from each other 120° in a clockwise direction. The three currents, A, B and C, of the second balanced system are of equal amperage but 120° out of phase. This system is called the positive sequence system of currents.

The third of the three balanced systems consists of three currents equal in magnitude but displaced from each other 120° in a counter-clockwise direction when the wires are taken in the same order as for the second system. The three currents, A_2, B_2 and C_2 are of equal amperage but 120° out of phase. This system is called the negative sequence system of currents.

In each case the rotation of individual vectors is the same.

Each of these three systems can be used independently of the others in the solution of a circuit, and the actual relations can be determined by superimposing the separate solutions.

Note that each of the three balanced systems of currents just described consists of three currents, and that one of these three currents is in each line. In the negative sequence system, for example, A_2 flows in line a, B_2 flows in line b, and C_2 flows in line c. In all, A_0, A_1 and A_2 flow in line a; B_0, B_1 and B_2 flow in line b; C_0, C_1 and C_2 flow in line c; and A_0, B_0 and C_0 flow in the neutral wire.

Since A, which is the actual current in line a, is equal to $A_1 + A_2 + A_0$, if the effects of A_1, A_2 and A_0 in producing voltage drops are calculated separately as though the other currents were not flowing, and the effects superimposed, the result will be the same as if conditions were determined with A itself flowing. In a similar manner, the voltage relations of the circuit can be determined for the other two phases, b and c.

Where there is mutual inductance between the various lines, as in the case of a transmission line, the solution is greatly simplified by this process. Formulae and tables are readily available giving the effective impedance of a line with balanced currents 120° out of phase and also with equal in-phase currents in each line. Similar formulae for unbalanced currents are not generally available, and if they were, the solution would still be of greater complexity.

Vector diagrams will be used to give a graphical illustration of this process, and in order to obtain quantitative results, complex quantity notation will be used.

Vectors

If an alternating current is represented by a vector, the length of the vector represents the value of the current in amperes; the position of the vector represents the time when the current reaches its maximum value in relation to the other vectors represented.

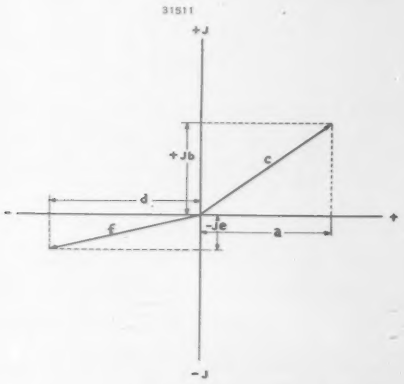


Fig. 1—Reference Axes for Complex Quantities

Complex Quantities

Fig. 1 illustrates the complex quantity notation used to represent vector quantities. It has been found that this notation can be used to represent vector quantities. Since the proof has already been given many times, it will be omitted in this article. In Fig. 1 the vector C is represented as the projection of the vector on the horizontal axis plus j times the projection of the vector on the vertical axis. (The vector must be placed with its beginning at the intersection of the horizontal and vertical axes, O.) In this figure it can be seen by inspection that $C = a + jb$. If the horizontal projection were to the left of the vertical line instead of to the right, the horizontal distance would be prefixed by a minus sign (—). If the vertical projection were below the horizontal line instead of above it, the vertical component would be prefixed by —j instead of +j; thus in Fig. 1, $f = -d - je$.

In like manner, any vector quantity can be represented by the sum of its horizontal and vertical components. These complex quantities can be multiplied, divided and in general subjected to the usual algebraic operations, as the solution of a specific problem may require.

It has been found that j in the complex quantity can be set equal to $\sqrt{-1}$. If $j = \sqrt{-1}$, then $j^2 = -1$, $j^3 = -\sqrt{-1}$, and $j^4 = 1$. These relations simplify the complex expressions obtained in the solution of problems involving these quantities.

Fig. 2 illustrates a 3-phase circuit with current A in line a, current B in line b and current C in line c. In Fig. 3, a graphical representation of the zero sequence components (A_0, B_0 and C_0) of these currents (A, B and C) is given. If $A_0 = I_0$, then $B_0 = I_0$, and $C_0 = I_0$, as shown in this figure. A_0 flows in line a, B_0 in line b, and C_0 in line c. All the currents are vector quantities.

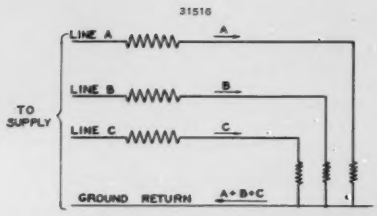
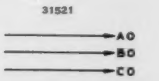


Fig. 2—Circuit Diagram

In Fig. 4 a graphical representation is given of the positive sequence components A_1, B_1 and C_1 of the currents A, B and C. If $A_1 = I_1$, then $B_1 = (-.5 - j\ .866)\ I_1$, and $C_1 = (-.5 + j\ .866)\ I_1$, since the currents A_1, B_1 and C_1 are equal but displaced from each other 120° in a clockwise direction.



Above—Fig. 3—Zero Sequence Components of Currents Flowing in Fig. 2

Right—Fig. 4—Positive Sequence Components of Currents Flowing in Fig. 2

Fig. 5 gives a graphical representation of the negative sequence components A_2, B_2 and C_2 of the currents A, B and C. If $A_2 = I_2$, then $B_2 = (-.5 + j\ .866)\ I_2$, and $C_2 = (-.5 - j\ .866)\ I_2$, since the currents A_2, B_2 and C_2 are equal but displaced from each other 120° in a counter-clockwise direction.

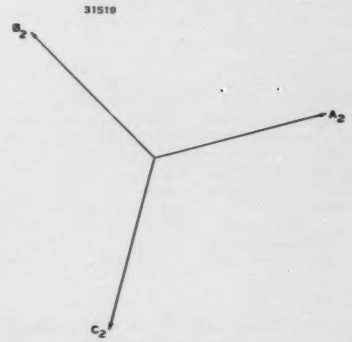


Fig. 5—Negative Sequence Components of Currents Flowing in Fig. 2

Since the current in line a is equal to A, and is composed of the components A_0, A_1 and A_2, this relation may be written:

$$A = A_0 + A_1 + A_2$$

Similarly:

$$B = B_0 + B_1 + B_2$$
$$C = C_0 + C_1 + C_2$$

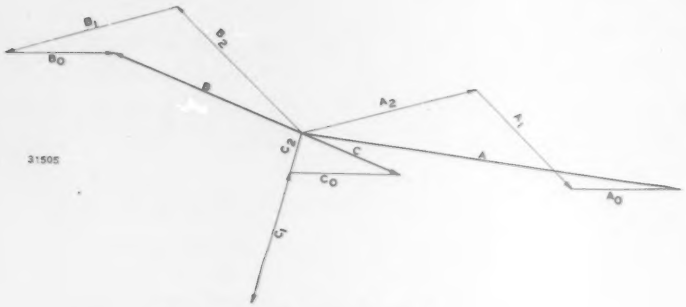


Fig. 6—Line Currents of Fig. 2

Using these relations for the graphical determination of A, B and C from their components, the currents of Fig. 6 are obtained.

Fig. 6 shows the unbalanced 3-phase system of currents (A, B and C) flowing in the circuit of Fig. 2, the symmetrical components of which are the currents of Figs. 3, 4 and 5.

Use of Multiplier "a"

In solving equations involving symmetrical components, it is often convenient to let the complex quantity $(-.5 + j.866)$ equal a. Then $a^2 = (-.5 + j.866)^2 = (-.5 - j.866)$.

Note that $1 + a^2 + a = 0$.

The positive and negative sequence system of vectors can then be represented as follows:

$$A_1 = I_1$$
$$B_1 = (-.5 - j.866)\, I_1 = a^2 I_1$$
$$C_1 = (-.5 + j.866)\, I_1 = a\ I_1$$
$$A_2 = I_2$$
$$B_2 = (-.5 + j.866)\, I_2 = a\ I_2$$
$$C_2 = (-.5 - j.866)\, I_2 = a^2 I_2$$

Thus, the positive sequence system of vectors A_1, B_1 and C_1 are respectively I_1, $a^2 I_1$ and $a I_1$.

The negative sequence system of vectors A_2, B_2 and C_2 are respectively I_2, aI_2 and $a^2 I_2$.

The use of the multiplier "a" in expressions involving symmetrical components is often useful as a labor-saving device. It is usually desirable to substitute its complex expression $(-.5 + j.866)$ when the final solution in terms of "a" has been obtained.

The relations existing between a system of unbalanced three-phase currents and its symmetrical components have been described in detail. The resolution of unbalanced voltages into their symmetrical components can be performed in similar manner; however, for electrical problems, it is generally sufficient to resolve only the currents into their symmetrical components. In general, the resolution of the voltages into their symmetrical components does not greatly simplify the solution.

Formulae for Resolving Three Unbalanced Vectors Into Their Symmetrical Components

The equations required for the resolution of three unbalanced vectors into their symmetrical components, together with the method of derivation, are given below. The three vectors are A, B and C as in Fig. 6. (All quantities are vector quantities.)

Let:

$$\text{Set No. 1} \begin{cases} A = A_0 + A_1 + A_2 \\ B = B_0 + B_1 + B_2 \\ C = C_0 + C_1 + C_2 \end{cases}$$

A_0, B_0, C_0 are the zero sequence components.
A_1, B_1, C_1 are the positive sequence components.
A_2, B_2, C_2 are the negative sequence components.

$$\text{Set No. 2} \begin{cases} A_0 = B_0 = C_0 \\ B_1 = a^2 A_1 \\ C_1 = a\ A_1 \\ B_2 = a\ A_2 \\ C_2 = a^2 A_2 \end{cases}$$

$$\text{Where} \begin{cases} a = -.5 + j.866 \text{ and} \\ a^2 = -.5 - j.866 \end{cases}$$

Substituting these values in the above equations:

$$\text{Set No. 3} \begin{cases} A = A_0 + A_1 + A_2 \\ B = A_0 + a^2 A_1 + a\ A_2 \\ C = A_0 + a\ A_1 + a^2 A_2 \end{cases}$$

Solving these equations simultaneously:

$$\text{Set No. 4} \begin{cases} A_0 = \tfrac{1}{3}\,(A + B + C) \\ A_1 = \tfrac{1}{3}\,(A + aB + a^2 C) \\ A_2 = \tfrac{1}{3}\,(A + a^2 B + aC) \end{cases}$$

The equations given above are the general equations for resolving three unbalanced vectors into three balanced systems. Set No. 4 is used when the unbalanced system is to be resolved into three balanced systems; set No. 1 is used to combine the solutions obtained after each set is considered separately. The most convenient way to represent the vectors is by the use of complex quantities.

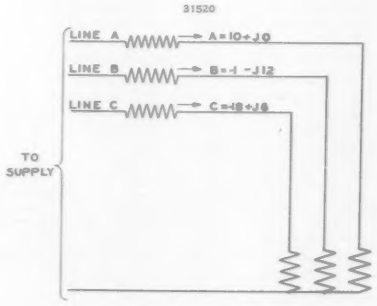


Fig. 7—Circuit Diagram

An example of the use of these equations follows: In Fig. 7, there are three unequal currents flowing. These three unequal currents will be replaced by three balanced systems by using the general equations given above:

In Fig. 7: Current $A = 10 + j0$
Current $B = -1 - j12$
Current $C = -18 + j6$

These are shown in the vector diagram of Fig. 8. Using the equations of set No. 4:

$A_0 = \tfrac{1}{3}\,(A + B + C) =$
$\tfrac{1}{3}\,(10 + j0 - 1 - j12 - 18 + j6) = -3 - j2$

$A_1 = \tfrac{1}{3}\,(A + aB + a^2 C) = \tfrac{1}{3}\,[10 + j0 + (-.5 + j.866)\,(-1 - j12) + (-.5 - j.866)\,(-18 + j6)]$

$A_1 = 11.70 + j5.91$

$A_2 = \frac{1}{3}(A + a^2B + aC) = [10 + j0 + (-.5 - j.866)(-1 - j12) + (-.5 + j.866)(-18 + j6)]$

$A_2 = 1.30 - j3.91$

$A_0 = B_0 = C_0 = -3 - j2$

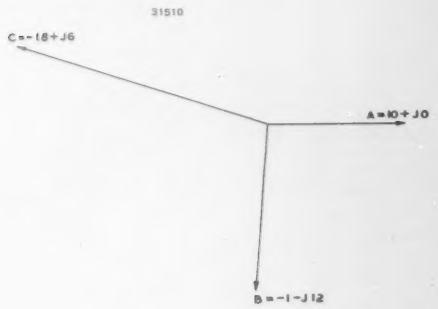


Fig. 8—Line Currents of Fig. 7

From equations of set No. 2:

$B_1 = a^2A_1 = (-.5 - j.866)(11.70 + j5.91) = -.74 - j13.08$

$C_1 = a\,A_1 = (-.5 + j.866)(11.70 + j5.91) = -10.96 + j7.17$

$B_2 = a\,A_2 = (-.5 + j.866)(1.30 - j3.91) = 2.74 + j3.08$

$C_2 = a^2A_2 = (-.5 - j.866)(1.30 - j3.91) = -4.04 + j.83$

The zero phase sequence components are shown in Fig. 9.

The positive phase sequence components are shown in Fig. 10.

The negative phase sequence components are shown in Fig. 11.

The correctness of the solution may be checked by substituting in the equations of set No. 1, as follows:

$A = A_0 + A_1 + A_2 = -3 - j2 + 11.70 + j5.91 + 1.30 - j3.91 = 10 + j0$

$B = B_0 + B_1 + B_2 = -3 - j2 - .74 - j13.08 + 2.74 + j3.08 = -1 - j12$

$C = C_0 + C_1 + C_2 = -3 - j2 - 10.96 + j7.17 - 4.04 + j.83 = -18 + j6$

Equivalent Circuits of the Three Components

Since the impedance of the circuit may be different to currents of positive, negative and zero sequence, it is necessary to set up the circuit involved three times, once for each of the three components. Each circuit will show the impedance which that circuit offers to the currents under consideration.

The sum of the three positive sequence currents equals zero, and so no part of this current flows in the neutral. This is also true of the negative sequence currents.

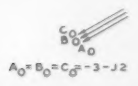


Fig. 9—Zero Sequence Currents of Fig. 7

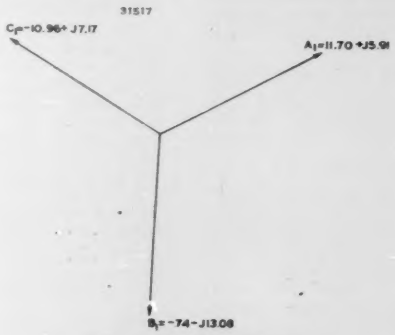


Fig. 10—Positive Sequence Currents of Fig. 7

Since the positive and negative sequence currents always flow in the lines, the circuit impedances can be represented as being in series with the lines in the equivalent circuits for them. The simplest and most direct method of determining the circuit impedance for positive sequence currents is to assume balanced 3-phase currents flowing in the system. The currents in the three lines will be equal in magnitude but out of phase with each other 120° in a clockwise direction when the lines are taken in the order a, b, c. The impedance of the circuit to such a system of balanced currents is obviously that of the familiar balanced 3-phase system.

The circuit impedance for negative sequence currents is obtained in similar manner by assuming currents out of phase with each other 120° in a counter-clockwise direction. For transmission lines, transformers and other static apparatus, the positive and negative sequence impedances are the same. For rotating machines, they are usually quite different.

Clearly, the positive sequence impedance of a transformer is the ordinary impedance of the transformer with power supplied to the primary and power taken from the secondary. It may be expressed in per cent or in ohms as is convenient.

When the transformers have been reduced to equivalent transformers with a 1 to 1 ratio, the positive sequence impedance can be placed in series with the lines. All three lines carry numerically equal currents. If the impedances in all three lines are equal, the numerical values of the positive sequence voltages for all lines are identical. The numerical values of voltage which apply to any line can be obtained by considering only one of the 3-phase lines as a single-phase line with the return circuit through a neutral wire of zero impedance. This single-phase diagram is really the diagram of one phase.

When an impedance or short circuit is placed between any lines, or lines and neutral of a system, this impedance should be considered as providing a return path for currents of all sequences. The actual load impedance can be replaced by fictitious impedances between all three phases.

The zero sequence currents are equal and in phase in all three lines. The current in the neutral is equal to the sum of the zero sequence currents in the three lines. That is, it is equal to three times the zero sequence current in any one line.

The simplest and most direct method of determining the circuit impedance for zero sequence currents is to assume equal in-phase currents flowing in the three lines. By tracing out the circuits, determination can be made as to whether there is a path for such currents, and, if so, what the path is. When the current flows through a transformer winding, the principle "the sum of the ampere turns on each leg of the transformer equals zero" will aid in determining the path.

In setting up the equivalent circuit diagram for zero sequence currents, the transformers can be conveniently reduced to a 1 to 1 ratio. The zero sequence currents may circulate in the windings without flowing

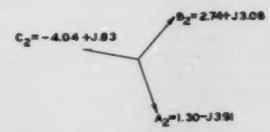


Fig. 11—Negative Sequence Currents of Fig. 17

through the lines; therefore, the transformer impedance is most conveniently represented by an impedance in series with the transformer winding, and the transformer winding is best shown as a perfect 1 to 1 ratio transformer without impedance. The flow of zero sequence current can be indicated on this diagram. If the impedance drops due to the current I_0 in each winding around the complete circuit are added taking one line and the neutral, and this sum divided by the winding current I_0, the impedance so determined may be used to set up a single-phase circuit for the zero sequence impedance, similar to the method indicated for the positive and negative sequence impedances.

In any case, when the circuits for the positive, negative and zero sequence components of the current are desired, the following procedure is recommended:

1. Draw a 3-phase diagram of the circuits involved.
2. Draw a new diagram for the positive sequence currents showing all impedances in series with the lines and the transformers reduced to a 1 to 1 ratio so that the circuits are coupled directly instead of being connected through transformers.
3. Repeat (2) for the negative sequence currents.
4. Reduce (2 and 3) to single-phase diagrams using only one line and a zero impedance neutral return.
5. Draw a new diagram for the zero phase sequence circuit, with transformer windings reduced to a 1 to 1 ratio and all zero sequence transformer impedances in series with the transformer windings. The coupling between the windings will be by means of the 1 to 1 ratio transformers.
6. Trace out the circuits showing the path of the zero sequence currents (equal currents in phase in each line). Where no path exists, mark the value of current O; where a path exists, assume a literal value of I_0 for the current in the transformer winding and mark the currents accordingly. For example, the current in the neutral of a star-connected transformer with a winding current of I_0 will be $3I_0$.
7. For the equivalent single-phase circuit of one line, with balanced impedances, trace the circuit from one line through the load to neutral, through the supply and back to the starting point. This circuit, with its impedance drops divided by the current I_0 and with the transformer coupling of circuits changed to conductive coupling, will represent the equivalent single-phase circuit for zero sequence current. Note that this places a neutral impedance Z_N in the circuit as $3Z_N$.
8. To determine circuit relations, reference should be made to the 3-phase circuit diagrams. The single-phase diagrams only partially represent the circuits. They do save time, however, when frequent use is made of them and their limitations and use have been verified from the 3-phase diagram.

The application of these principles to the most common transformer connections will be shown, in order to demonstrate their use and to provide material for reference.

Two-Winding Transformers

For all two-winding transformers the positive and negative sequence diagrams are the same. The series impedance is always equal to the impedance between the two windings. This impedance is commonly measured by short-circuiting one winding and applying voltage to the other winding sufficient to cause rated current to flow in the windings. The per cent impedance of the transformer is equal to the impedance volts $\times$ 100 $\div$ (rated voltage of windings to which voltage is applied).

The three-phase equivalent circuit for the positive and negative sequence currents of a two-winding transformer, for either delta, star or zigzag connection of the windings, is shown in Fig. 12a. The single winding circuit is shown in Fig. 12b.

Fig. 13 shows the equivalent circuits for the zero sequence currents of two-winding transformers with various connections.

For delta-delta connection shown in Fig. 13a, no zero sequence current can flow in the lines, since there is no connection to the neutral of the system. The zero sequence current can circulate inside the two deltas only.

For delta-star connection, shown in Fig. 13b, note that if the neutral of the star-connected transformer is underground, Z_N becomes infinite, and the impedance to zero sequence current is infinite.

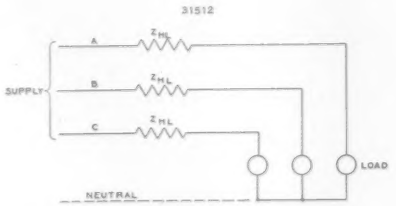


Fig. 12a—Equivalent 3 phase Circuit of a Two Winding Transformer

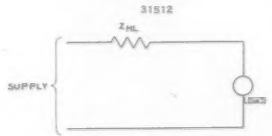


Fig. 12b—Equivalent Circuit of One Phase

Equivalent Circuit Diagrams of a Three Winding Transformer for Positive and Negative Sequence Circuits

For star-star connection, shown in Fig. 13c, note that if any of the neutrals shown become ungrounded, the impedance to zero sequence current is infinite, and no zero sequence current can flow.

The positive and negative sequence diagrams for zigzag-delta and zigzag-star transformers are the same as Fig. 13a and 13b. The zero sequence diagrams are shown in 13d and 13e. Note that no zero sequence current flows in the delta windings of 13d or in the star windings of 13e. The zero sequence diagram of a zigzag grounding transformer with no secondary is the same as shown in 13d if the delta winding is ignored. A zigzag grounding transformer without a secondary winding carries no positive or negative sequence current in its windings, although such currents may flow in the lines to which it is connected.

Three-Winding Transformers

For three-winding transformers with delta or star windings, the positive and negative sequence diagrams are always the same. The three-phase equivalent cir-

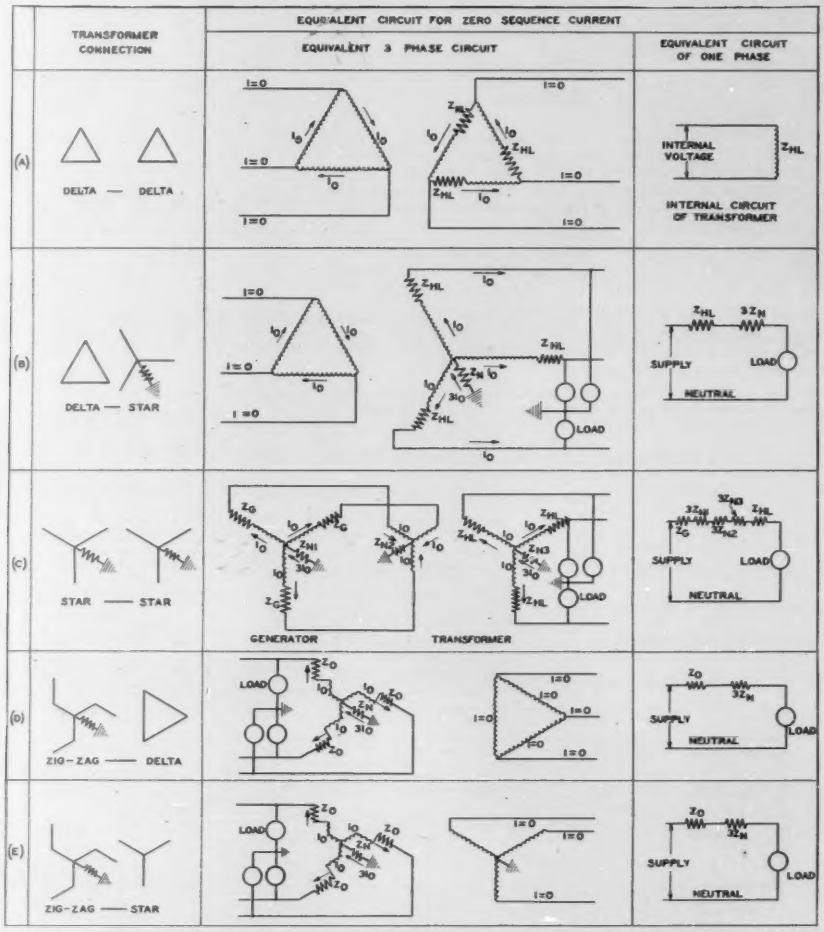


Fig. 13 — Equivalent Circuits of Two Winding Transformers for Zero Sequence Currents

cuits for positive and negative sequence diagrams are shown in Fig. 14a. The single-phase equivalent circuit is shown in Fig. 14b.

Where the three windings are delta-connected, as in Fig. 15a, no zero sequence current can flow in the lines. The only path for zero sequence current is in the transformer windings.

Where there are two delta-connected windings and one star-connected winding, as in Fig. 15b, the zero sequence currents flowing to ground will divide between the two delta windings in inverse proportion to their impedances.

The equivalent diagram for a three-winding transformer with two star-connected windings is shown in Fig. 15c. Note that if the impedances in either neutral becomes infinite, no zero sequence current will flow in that circuit.

The equivalent diagram for a three-winding transformer with three star-connected windings is shown in Fig. 15d. If the impedance in the neutral of the generator or of the high voltage is infinite, no zero sequence current can flow in any of the circuits of Fig. 15d.

The impedance of transformers having other connections to currents of positive, negative and zero sequence can be calculated by assuming balanced currents of each sequence flowing in the lines, or the impedance may be measured on test by causing balanced currents of the desired sequence to flow in the lines.*

Transmission Lines

The positive and negative sequence impedances of a transmission line are the same, and are determined by assuming balanced currents 120° out of phase with each other in the three lines. The zero sequence im-

*For the separation of the impedance of a three-winding transformer into three portions, one belonging to each winding, refer to the article entitled "Three and Four Winding Transformers" in the September, 1936, issue of the Allis-Chalmers Electrical Review.

pedance of a transmission line is the impedance with the three lines carrying equal in-phase currents which return through the ground.

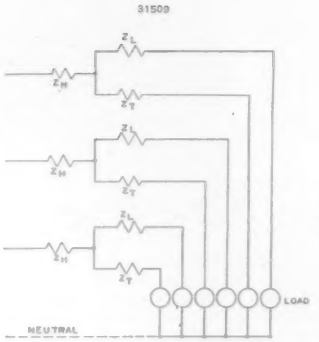
Rotating Machines

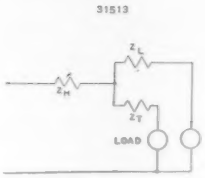
For rotating machines, the values of positive, negative, and zero sequence impedance are all different. The positive sequence impedance is the impedance with balanced currents which are 120° out of phase with each other and which have the same time sequence as the terminal voltages.

The negative sequence impedance is the impedance with balanced currents which are 120° out of phase with each other and which have the time sequence opposite to that of the terminal voltages.

The zero sequence impedance is the impedance with equal in-phase currents in each line, with the currents returning through the neutral.

Another article on "Symmetrical Components Simplified" will appear in a later issue of the Allis-Chalmers Electrical Review.





Equivalent Circuit Diagrams of a Three Winding Transformer for Positive and Negative Sequence Circuits

Fig. 14a (Left)—Equivalent 3 Phase Circuit

Fig. 14b (Above)—Equivalent Circuit at One Phase

3150

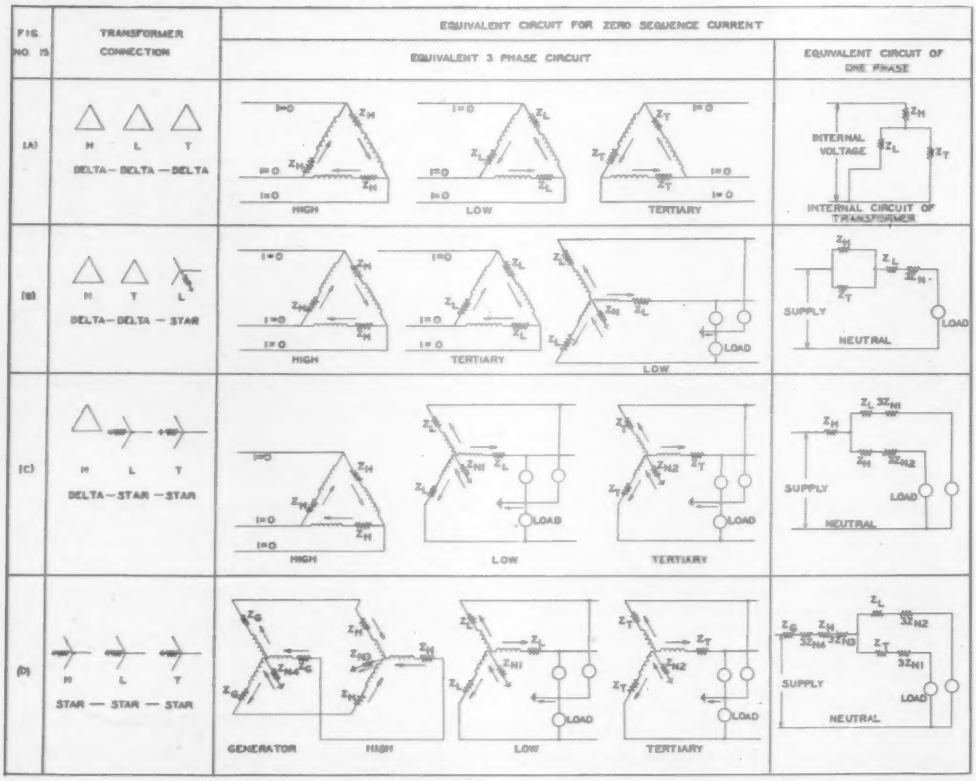


Fig. 15—Equivalent Circuits of Three Winding Transformers for Zero Sequence Currents

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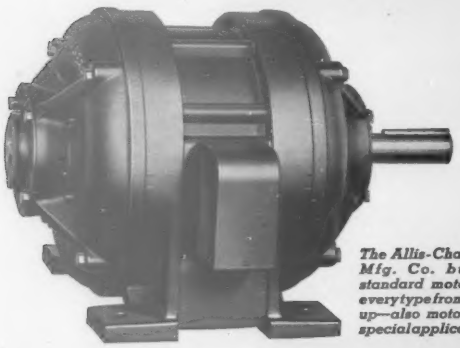

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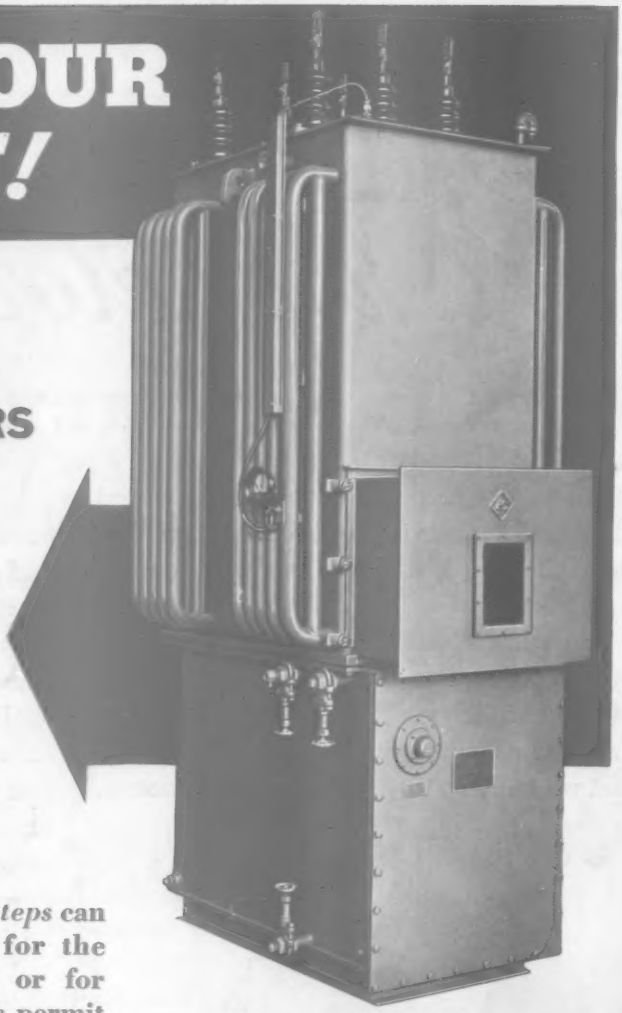

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